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ECO-POWER FROM PLASTIC

Generating electricity from plastic – can you even do that? Professor Lukas Schmidt-Mende is firmly convinced you can. He intends to have solar cells made from plastic ready for production in the near future. After all, plastic doesn't have to be an insulator: it can very well act as a semiconductor – and is extremely cheap, to boot. Physicist Schmidt-Mende wants to exploit all of these properties, and expects the breakthrough that will allow eco-power to be generated from plastic to come in just a few years.

The Germans are world champions in women's soccer, handball – and garbage separation. Nothing boggles the non-German mind as much as the German passion for bio-waste containers and the like. And their particular favourite: the *yellow bag.* Into this bag, the Germans neatly sort their plastic waste, which is then expedited by rail to Bremen or Hamburg, where it is loaded onto large container ships to embark for the Far East. The Chinese then make fleece sweaters from this plastic waste and, in their turn, export them back to Germany to sell at a higher price. Refining raw materials was once a German domain. And yet the majority of the meticulously separated plastic is – in the parlance of German Officialese – "sent for thermal recycling": it is burnt as fuel. After all, plastic has a very similar calorific value to mineral coal. But burning plastic is ecologically controversial. All that can change, says Professor Lukas Schmidt-Mende. He intends to obtain energy from plastic. And how? By making solar cells out of all this neatly sorted plastic. LMU is equally impressed with this idea. Thus in Autumn 2007, after study and research visits to Cambridge and Switzerland, the young experimental physicist of only 35 years was called to Munich to be appointed associate professor.

But how can electricity be generated from plastic? In order to make it understandable to the layman, the young physicist granted this journalist a private lesson in physics. The principle is easy, Lukas Schmidt-Mende explains, and it is all around us – in diodes, for example. A diode is an electrical component made of semiconductors; the electricity only flows in one direction. Semiconductor is the term used for crystalline solids that possess both conductive and non-conductive properties. Basically, the conductivity of semiconductors is temperature-dependent. While semiconductors act as insulators when cold, their electrical conductivity rises as their temperature rises. This property of semiconductors is most easily explained by the "energy band model". In crystals, electrons will exist at various different energy levels. In chemistry, we learn that electrons always like to orbit an atomic nucleus in pairs. The orbits of the electrons around the nucleus are referred to as "shells" – a misleading name, since these "shells" only refer to potential but not real spaces where the electrons can reside.

The closer the electrons are to the atom's nucleus, the lower their energy level will be. Because of this, they are more strongly bound to the nucleus, and can hardly move. The electrons further away from the nucleus, however, are freer to roam and are available to transport electrical charge. The last level at which all electrons are bound is called the "valence band". An energy level with free, binding-happy electrons, on the other hand, is called a "conduction band". These two bands overlap in conductive materials such as metals. So metals have many free and very easily movable electrons in the conduction band. Yet it is possible for a wide gap to exist between the valence band and the conduction band. And in insulators, for example, the valence band is fully occupied while the conduction band is empty. The gap in the band prevents electricity from flowing.

▲ Example cells of all different colours due to the different organic materials used.

ELECTRON SEEKS PARTNER

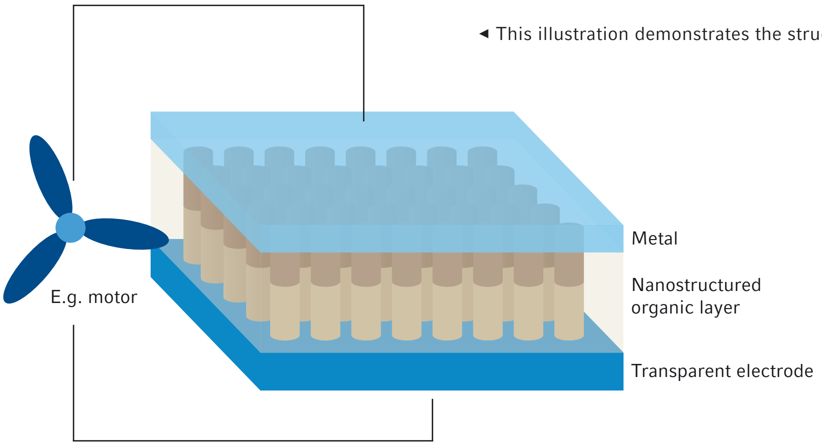
But what is the story with semiconductors? The semiconductive nature of a crystal such as silicon is above all a result of its energy gap. At temperatures close to absolute zero – minus 273 degrees Celsius – the valence band of the semiconductor is fully occupied and the conduction band is empty. If you excite an electron enough, then it will separate from its partner. It will become free and – like most singles – immediately seek out another partner. As the heat increases, ever more electrons leave the valence band. But they do not fully make the jump to the conduction band, since they don't have enough energy. The electrons can only find a new target if the material has been "doped", or contaminated as it were. In semiconductors, unlike in metals or insulators, a certain number of electrons can be present in the energy gap, depending on the temperature. For many physical applications, this "intermediate" state is of great advantage. The occupied gap is the drive behind solar cells, for example. The electrons in the gap are freer to move, and so the electrical conductivity of such crystals is higher.

Those who may have preferred to pay more attention in literature than in Physics at school might perhaps be reminded here of Goethe's novel *Elective Affinities.* In the fourth chapter of the first part, Eduard, Charlotte and the Captain have a famous dispute where they try to describe the realm of human relations using only chemistry metaphors. It goes like this: "In all natural objects with which we are acquainted, we observe immediately that they have a certain relation to themselves. […] As everything has a reference to itself, so it must have some relation to others. […] And that will be different according to the natural differences of the things themselves." And yet we can see, Eduard in Goethe's novel explains, that different natures can reconcile their differences, given that there are "intermediate members in our chemical world which will combine elements that are mutually repulsive." The Captain rejoins by saying "Such natures as, when they come in contact, at once lay hold of each other, each mutually affecting the other, we speak of as having an affinity one for the other. With the alkalis and acids, for instance, the affinities are strikingly marked. They are of opposite natures; very likely their being of opposite natures is the secret of their interrelational effect – each reaches out eagerly for its companion, they lay hold of each other, modify each other's character, and form in connection an entirely new substance. There is lime, you remember, which shows the strongest inclination for all sorts of acids – a distinct desire of combining with them!" And Charlotte concludes with "It is the way in which we see all really deep friendship arise among men, opposite peculiarities of disposition being what best makes internal union possible." And yet sadly, Goethe reminds us, that which unifies also separates: "Affinities begin really to interest only when they bring about separations." Goethe uses chemistry to explain the powers of Eros and the human impulse towards infidelity. And yet it also goes the other way. After all, the force behind the bond-forming desire of elective affinities is called, in chemistry and physics: the electron. In that electrons, like Goethe's novel heroes, are "unfaithful", they leave "holes" behind in the valence band – lovesickness, so to speak. If one "flirts" with a semiconductor – if one feeds it energy in the form of light or heat, perhaps – then more electrons disengage themselves from the valence band. The resistance of the semiconductor drops; it becomes more conductive. But if one interrupts the supply of energy, then the electrons fall back to the valence band and "recombine" with their former partners. Old love never dies after all.

MANIPULATED CRYSTALS

Let us come back to the solar cell: solar cells convert sunlight into electrical energy. This photovoltaic effect was discovered in 1839 by Alexander Becquerel. In order to create a photovoltaic effect, one needs a so-called p-n-junction. The p-n-junction occurs when two differently doped semiconductor materials are combined together. A solar cell consists of doped silicon crystals. That means that the crystals have been manipulated so as to create two layers that act as different poles: the p-type semiconductor (anode) and the n-type semiconductor (cathode). The n-type semiconductor has the electrons and the p-type has the holes. This different charge is achieved by treating the silicon atoms with just a few atoms of another element. The n-type layer, for example, can be produced by adding phosphorus atoms and the p-type layer by adding aluminium atoms.

But why phosphorus and aluminium? Phosphorus atoms, we remember from chemistry, are "pentavalent". That means they have five so-called valence electrons in the outermost orbit. These are available for making chemical bonds with other elements. Four of these five



◂ This illustration demonstrates the structure of a solar cell.

electrons get built into the silicon crystal, but one electron remains free. It is only very weakly bound to the atomic nucleus, and can be removed with just the slightest addition of energy. As such, phosphorus is happy to give away its free electron, so we call it a “donator”. It works in reverse with aluminium. Quite the opposite of phosphorous, aluminium has five holes, of which again only four get incorporated into the crystalline structure. The fifth hole waits for a free electron, such as the one from the phosphorus. That makes aluminium an “acceptor”. By carefully “contaminating” the silicon crystal with donators and acceptors, we increase their electrical conductivity. This is called doping. Goethe would have called it eroticism.

NO GOING BACK TO A FORMER PARTNER

Solar cells normally consist of differently doped silicon compounds. If a light beam – a photon – now strikes the space charge region or “void”, then it separates the electron and hole by exciting the electron, lifting it to a higher energy level. Now free, the electron is pulled towards the n-conductor and, in turn, the hole towards the p-conductor. A special barrier layer prevents the charge carriers from recombining. Instead of letting the electrons return to their former partners, they are forced outward. They have to flow through the circuit and do work. So it is work first and then play. Seeing as not every photon can bring about a separation, however, and seeing as not every free electron can be prevented from returning, the efficiency of solar cells is limited: a maximum of 30 percent is possible. And that is only in the high-tech products that are extremely difficult to produce, and therefore extremely expensive, and which only get used in the aerospace industry. Normal solar cells reach an efficiency of 10 to 18 percent, and even they are costly and difficult to produce. That is why Lukas Schmidt-Mende feels it is high time we took a new road and left our old attitudes behind us.

And so, we see the young professor in his newly established laboratory in the physics department testing new semiconductors – such as plastic. Plastic is not necessarily an insulator, as most would probably imagine. It can very well act as a semiconductor. Plastic is a product of organic chemistry and consists of hydrocarbon compounds. There are conjugate polymers, for example, that can act as donators, and fullerenes that happily act as acceptors. The semiconductive or even metal-like properties of plastic are due to delocalized, homeless, vagabonded electrons that become free from double or even multiple bonds between the carbon atoms. In 2000, this discovery was even rewarded with the Nobel Prize. While the efficiency of solar cells produced from plastic is still only about five percent, its advantage is obvious, the physicist says: plastic can be produced cheaply and easily and above all on an industrial scale – basically by the gallon. Of course, that applies just as much to plastic solar cells. If you put them in polymer solution in the form of ink, you can even print them with an inkjet printer. The air conditioning system in your car, for example, could get its power from the green-tinted sun visor on the windscreen. Since the polymer solution can be produced in just about any colour, even building facades could serve as solar collectors. Or tiny powerhouses in window panes are conceivable, that absorb light, generate electricity and still remain transparent. Or light, flexible, roll-up solar cells – your laptop will never be that big, clunky old *"schleptop"* ever again.

So that these applications progress beyond science fiction, physicists now have to endow the plastic cells with an ideal morphology, a spatial structure. Lukas Schmidt-Mende's goal is to get the space charge regions to overlap in a certain way by creating an appropriate 3D nanostructure. To do this, he anodizes aluminium foil in an acid bath. He pours metal oxides into the pores this creates and then etches the corroded aluminium oxide away. The physicist then fills the nanotubes thus created with inorganic material. The plastic solar cell is now complete. The LMU physicist is confident he will make the breakthrough that will allow eco-power to be generated from plastic in just a few years. Now that's a physics lesson worth listening to.

Prof. Dr. Lukas Schmidt-Mende has been a professor within Functional Nanosystems at the Faculty of Physics since 2007. There, he heads a workgroup in the field of hybrid nanostructures in the cluster of excellence „Nanosystems Initiative Munich" (NIM) and is member of the Center for NanoScience (CeNS).
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