

SOLAR ENERGY – TECHNOLOGICALLY ADVANCED – ECONOMICALLY PROFITABLE – ECOLOGICALLY COMPATIBLE

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The growing environmental awareness of our society initiated a concern for ecological and sustainable energy production. Despite a huge amount of research on many different fields the most promising source of clean and safe energy still is the sun which made possible the development of life itself. Furthermore, there is virtually unlimited supply of sunshine compared to our present sources of energy; the deposits of fossil energy will fail our growing demand within a few decades and show serious impact on the environment. At the moment we are only beginning to feel the consequences like global warming or smog in the cities.

Clean sources of energy like wind, water and bio-mass have been used for long times and are well established sources of energy. Present technological developments offers to a more and more efficient use. However, the direct conversion of sunlight into electricity with the help of photovoltaics is a rather new technology. Its application was boosted by the space age because the sun is the only safe source of energy for satellites. However, for many years solar cells were too expensive for terrestrial applications.

The growing production of solar cells over the last few years led to lower prices which make them a more and more attractive choice of off-grid applications and some grid-connected power plants. Annual growth rates of between 15 and 20 percent are now observed for solar modules. In 1997 the total sales rose by even 32 percent to a total of more than 110 MW_p. The sale is counted by the power output in Watt and the subscript p is an abbreviation for *peak*, which means the maximum power generated under ideal sunshine.

COSTS

The raw material for conventional solar cells, silicon, is a major part of the earth crust and therefore very cheap. It is the processing which makes silicon solar cells expensive. Silicon has to be thoroughly purified, bulk crystals must be grown, considerable loss occurs when they are sawed into slices, and time-consuming batching is required for processing. Finally, the individual solar cells must be soldered into strings and encapsulated into modules. Thus the manufacturing costs of a standard crystalline silicon module are about 3.3 Euro/W_p.

Competitive power prices of 0.12 Euro/kWh can only be obtained if the module costs can be reduced to below 0.8 Euro/W_p.¹⁾

Alternative sources of energy have been studied and amorphous silicon (a-Si), cadmium-telluride (CdTe), or copper-indium-gallium-diselenide (Cu(In,Ga)Se₂, CIGS) showed their potential for a cost-effective production of solar cells.²⁾ One of the most striking advantages of these materials is their high light-absorption. A layer of only three or even two microns of these materials absorbs light. That is why they are called *thin-film solar cells*. In comparison, crystalline silicon cells must be a hundred times thicker, i.e. a third of a millimeter for sufficient absorption of light.

A second advantage of thin-film solar cells is important in production. Amorphous silicon, CdTe, and CIGS are easily deposited by so-called thin-film processes. Once developed on a small scale in a laboratory, such processes can be scaled up to high-production volumes with the established technology of the coating industry. For example, antireflection coatings on windows are deposited with high uniformity on square meters. The series connection on thin-film cells can be done between the process steps by mechanical or laser scribing, which also lend themselves to upscaling.

Thus cost estimations of thin-film modules are based on a lower input of materials and the amount of production capacity. The cost of thin-film modules are between 1 and 1.7 Euro per W_p for production volumes in the range of 10 to 100 MW_p per year. Higher production volumes of about 500 MW_p/year would bring the module costs down to 0.3 to 0.5 Euro/W_p, which is well in the range of competitive power prices.

From an ecological point of view, thin-film solar cells have much to recommend them. A good way to judge ecological compatibility is the energy payback time, the length of time it takes a module to deliver the amount of energy which was used for its production. With silicon modules it takes several years, depending on the method of production. The projected energy payback times of thin-film modules are well below one year, usually in the range of two to six months. It is interesting to note that the supporting glass sheet is responsible for a major part of the energy input.^{3),4)} Thus thin-film solar cells are superior to crystalline silicon cells, economically as well as ecologically.

Modules from a-Si are already in production at several sites such as NAPS (Neste Advanced Power Systems, France), SANYO (Japan), PST (Phototronics Solarteknik, Germany), USSC (United Solar Systems Corporation, USA). CdTe modules are produced at Solar Cells Inc. and Golden Photon (both USA), BP Solarex and Matsushita (Japan). A module plant for CdTe is under construction at ANTEC Solar, Germany. It is expected to be in operation next year, 2000.

Siemens Solar officially announced the availability of their CIGS modules at the Second World Congress on Photovoltaic Solar Energy Conversion in Vienna, 1998. Würth Solar is a joint-venture of Würth and the Center for Solar and Hydrogen Technology (ZSW) in Stuttgart, Germany. They expect their module plant to be operative in the course of the current year, 1999. Figure 1 shows the in-line evaporation system and finished CIGS modules of the pilot plant at ZSW.

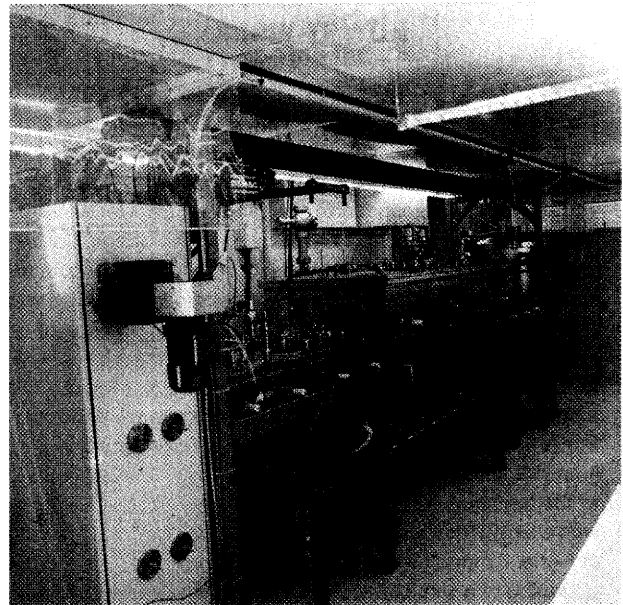


Figure 1 (b): Continuous evaporation system for the deposition of Cu(In,Ga)Se_2 layers at the ZSW (Photographs reproduced with the kind permission of the ZSW)

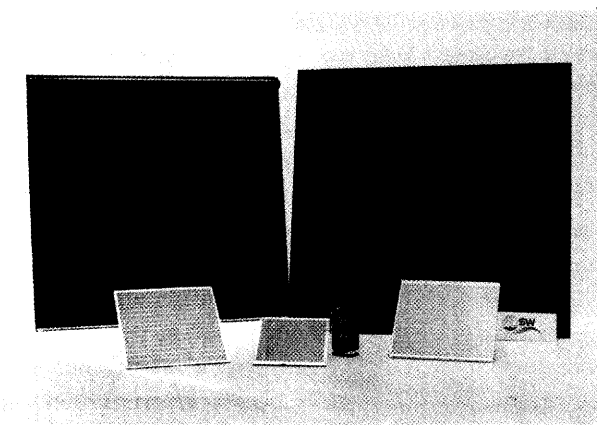


Figure 1 (a): Cu(In,Ga)Se_2 thin film solar modules produced at the Center for Solar and Hydrogen Technology (ZSW), in Stuttgart, Germany (Photographs reproduced with the kind permission of the ZSW)

HEALTH AND ENVIRONMENT ISSUES

A concern frequently raised in connection with CdTe and Cu(In,Ga)Se_2 is the toxicity of the materials used, especially cadmium. However, the hazards presented by a given material depend on the physical and chemical state and on the mode of exposure. It is essential to differentiate between the toxicity of cadmium in the metallic form and the toxicity of its compounds. Many consumers freely use and carelessly dump nickel-cadmium batteries, which contain metallic cadmium with an unreliable sealing. In contrast, CdTe and CdS are stable compounds whose properties have been thoroughly studied and which can cause no serious concern.

In a PV module CdTe is tightly sealed against any leakage by glass plates and epoxies. The health of workers at the CdTe module plant of Golden Photon Inc. has been carefully monitored over many years. It was reported that "no significant increases in worker exposure

have been observed". Compared to their deposition method, spray pyrolysis, other techniques such as electrodeposition or vacuum evaporation are much safer from the point of occupational exposure. Normal precautionary and protective measures as required in any industrial plant are sufficient for the CdTe module manufacturing plants and workers.^{5), 6)}

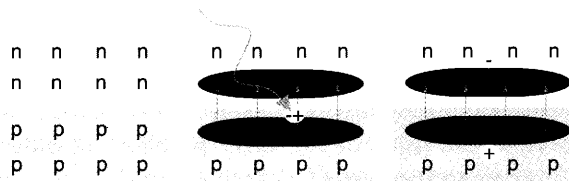
The Brookhaven National Laboratory (BNL) and the National Renewable Energy Laboratory (NREL), both in USA, have been studying these issues for many years. European institutions are collaborating with BNL in the study of the safety problems of different materials and processes for obtaining the Toxicity Characteristic Leaking Procedure certification (TCLP) of the US Environmental Protection Agency (EPA). CdTe modules (BP Solar modules of $30 \times 30 \text{ cm}^2$) have passed the appropriate EPA and European tests and are certified as non-hazardous waste. They are suitable for disposal in normal landfill sites. For comparison, fluorescent lights and computer screens do not pass these tests. Much better will be, of course, the recycling of CdTe modules after their expected lifetime of 20 to 30 years.

A second environmental concern is the availability of raw materials for high module production. With CdTe the critical material is tellurium, of which about 28 tons are required to produce 500 MW_p . The worldwide annual production amounts to 400 tons. The case is similar with CIGS, as the production of 500 MW_p would require 25 tons of indium of an annual output of merely 180 tons. The production volume of 500 MW_p could be attained within six or seven years at the present rate of expansion. Thus the production

HOW IT WORKS

Two concepts of semiconductor physics are essential for the understanding of solar cells: the *bandgap*, and *p- and n-doping*. The bandgap is a result of the bonds between the atoms. The atoms in a semiconductor need all their outer electrons (valence electrons) to bond to their neighboring atoms. For example, silicon has four valence electrons and bonds in a tetrahedral configuration with four neighbors. So in principle there are no free electrons to transport any current. However, if an electron is provided with a certain amount of energy it can leave its place in the bond and move around freely. It is exactly this amount of energy which is called bandgap energy. If the electron is not supplied with sufficient energy to cross this bandgap it cannot leave its place. Lattice vibrations which correspond to the temperature of a given solid can provide the electrons with energy. That is why semiconductors are more conducting at higher temperatures different from metals.

Doping of a semiconductor roughly means the introduction of an atom on a site where it does not fit. If an atom of a perfect lattice is replaced by an atom with one more electron (e.g. silicon replaced by phosphor) then this electron is not needed for the bonding. It can move away from its core and contribute to the transport of the charge. A similar situation arises if the atom introduced has one electron less (usually, boron instead of silicon). Now one bond is not saturated and if by any chance an electron in the neighborhood has enough energy to leave its own bonding site it can take the position left open, leaving a so-called hole at its original site. In both cases a charge is transported, either by additional electrons (negative charge carriers) or by missing electrons which can be described as positive charge carriers. The two cases are referred to as n- and p-type conductivity, respectively.



If layers of different conductivity type are in contact, a so-called p-n junction is formed. The electrons of the n-material show a certain tendency to slip into the holes of the p-material on the other side of the junction. This is called recombination. Every electron which moves across the junction carries a negative charge, leaving the positive core behind. This builds an electric field which works against further movement and eventually stops it. In the figure above the positive and negative charges are displayed as red and blue areas respectively. The resulting electrical field is represented by orange arrows.

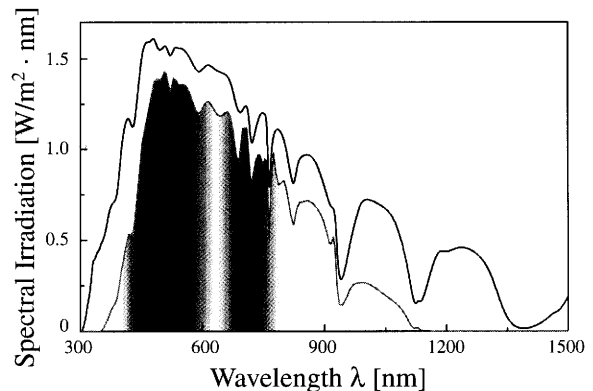
If the p-n junction is illuminated, a part of the light has enough energy to create a hole and push the electron over the bandgap. Now the electron is free to move, preferentially in the direction of the electric field. Similarly, the hole will move in the other direction. Thus the electron-hole pair is separated and the respective charges move to the contacts. The resulting current can drive an electric consumer.

WHAT HAPPENS TO THE LIGHT?

To the human eye sunlight appears white, but in fact it is a mixture of different colors, as can be observed in the rainbow. The intensity of the respective colors are represented by the blue curve of the diagram in the figure below. Wavelengths of around 300 nm belong to ultraviolet. The rainbow colors are between 400 and 800 nm. "Light" with longer wavelengths is called infrared.

The grey curve in the diagram represents the part of sunlight which is used by the solar cell. All the short wave lengths are absorbed, but the infrared part with more than 1100 nm is not suited to excite an electron to cross the bandgap. It can travel to the metallic back contact where it is reflected, then cross the solar cell once more and leave it through the window layer. A certain part, of course, will contribute to lattice vibrations and heat up the whole structure.

The remaining part of the sunlight can lift an electron across the bandgap. However, the light will give all its energy to the electron even if only a part of it is needed for crossing the bandgap. This could be considered as some extra "speed" which is lost as soon as the electron bumps into atoms on its way to the contact. In the end, the extra energy is lost to lattice vibrations and therefore to heat.



Thus, not all the energy of the sunlight can be converted to electric power, either because it has not enough energy for an excitation or it has too much and the excessive part is lost. The outlined absorption mechanism limits the maximum obtainable efficiency to below 30 percent. Higher degrees of efficiency can be obtained by using so-called tandem cells where two absorbers of different bandgaps are used for the conversion of the respective parts of the light.

of photovoltaics would consume a considerable part of the present quantities available of these two elements. Nevertheless, at the present state of things, the production of several GW_p of photovoltaic modules is possible and this opportunity should not be missed. Recycling after the expected lifetime is a way to recover the rare materials in the future.

CdTe AND CIGS THIN-FILM SOLAR CELLS

The Swiss Federal Institute of Technology (ETH) in Zurich has been developing solar cells based on CdTe or GIGS because these two thin-film materials combine the advantages of high efficiency and extraordinary long-term stability. The efficiency of modern cells based on CdTe or CIGS is comparable to crystalline silicon solar cells. ETH Zurich is participating in the JOULE program of the European Union where several projects are devoted to research and development in the field of renewable energy.

In principle, the production of solar CdTe solar cells is very easy. The substrate, glass covered with a transparent conducting oxide, is commercially available. On top of that a buffer layer of cadmium-sulfide is deposited either chemically or by evaporation in vacuum. The CdTe absorber is a very forgiving material; more than ten different methods can be used for its deposition. The best performance is obtained with tin-oxide front contacts and a vacuum-deposited CdTe layer. Additional intermediate annealing treatments are necessary to increase the efficiency. Tin-oxide and cadmium-sulfide are natural n-type semiconductors and effectively make a p-n junction with CdTe which is p-type after the annealing. A more detailed description of the underlying physics is given in the appendix. Materials for the back contact are being investigated at ETH. Figure 2 shows an electron-microscope image of a cross section through a typical CdTe solar cell.

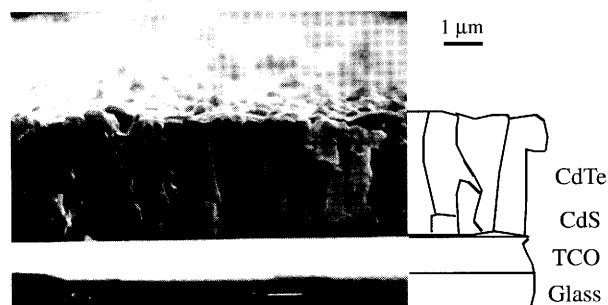


Figure 2: Cross section of a CdTe solar cell imaged with an electron microscope at a magnification of 10,000. The stack consists of a transparent conducting oxide (TCO), a cadmium-sulfide layer (non visible) and the CdTe Layer. The metal contact on top is outside the imaged area.

Efforts in the further development of CIGS solar cells are directed to deposition processes and deposition on

new kinds of substrates. The best results so far have been obtained by depositing the absorber on molybdenum-coated glass. Figure 3 shows a cross section through such a CIGS solar cell. The supporting glass and the molybdenum back contact can be seen in the bottom part. On top of it lies the p-type CIGS absorber. The n-type window (not visible at this scale) consists of a cadmium-sulfide buffer and the transparent front contact.



Figure 3: Cross section image of a CIGS solar cell. The different layers are clearly distinguished; molybdenum at the bottom with very small grains, vertical structures of the absorber and flat grains on the top which make the front contact.

In a solar module a second glass plate is used to protect the layers from environmental impact such as rain or hail. However, as outlined in the preceding section, the glass plate makes up a considerable part of the cost. Neither is the lower part really needed in this structure. A reversal of the structure is being tried to reduce the cost. First the front contact is deposited on the glass, then the buffer is added and on top of that the absorber and the metal back contact. Thus the glass which is needed for support during the deposition is also used as protecting material in the final module. For additional protection, the back can be covered with a stable polymer.

Another way of development is being pursued in the production of flexible solar cells on thin foils. However, the handling of foils as well as the control of the temperature poses some difficulties on the deposition process, especially in the vacuum. In the standard process the supporting glass levels out the inhomogeneities of the heating and thus ensures a uniform layer quality. In order to resolve these problems at ETH a process was developed where the whole solar cell can be removed from the supporting glass after the growth (see Figure 4). This solar cell showed the highest reported performance of a flexible solar cell. The efficiency of 12.8% was confirmed independently by a certified measurement at the Fraunhofer Institute for Solar Energy Systems in Freiburg (Brsg.).

The advantages are obvious; the standard high efficiency process on glass can be applied and the substrate

can be used for the next deposition. The cells can be adopted to any purpose, if flexibility is not required, they can even be glued to a low-cost, steady substrate.

This opens a variety of new applications. One of them is sun blinds which are simply rolled away when there is no sunshine and when energy production is low anyway. Flexible cells are not restricted to flat surfaces; they could easily be mounted on roof tiles. Naturally, solar cells without the heavy glass are preferred wherever weight is an issue. The possibilities range from solar-driven vehicles to communication satellites where every single gram counts.

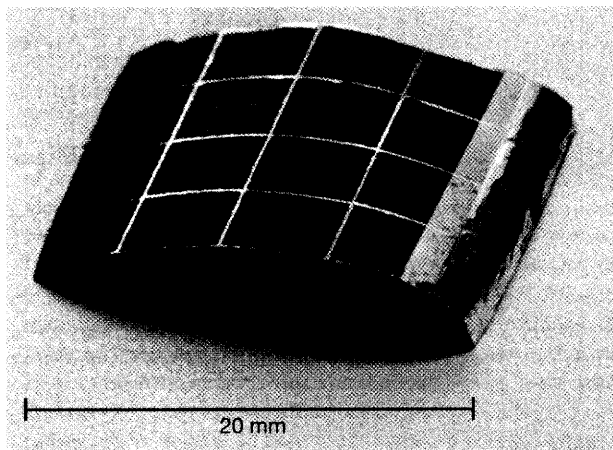


Figure 4: Flexible CIGS solar cell after removal from the glass substrate.

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