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Final Report on the Charmey Workshop (Part III):

Outcome of Group Discussions

This part contains the results of the most important event of the workshop, namely the discussions in freely chosen groups. The format of the reports has been defined by the groups also, following only very general guidelines. Thus, sometimes the authors mentioned are the members of a group, in other instances a rapporteur had been designated by the group as the author. Some groups chose to attribute specific ideas to the individual that forwarded them first by indicating its name at the beginning of the corresponding paragraph. – During review of the draft report, participants had the opportunity to express their support of ideas developed in other groups. These declarations of support are added at the end of each report.

Long-Range Photovoltaic R&D Concepts

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1. Background of Conventional Solar Cells

Solar-cell technology has moved strongly into commercial development and thus most solar-cell research and development does not fall under the category of long-term R&D. However, it is useful to point out some of the current topics of interest as they relate to solar-cell R&D.

Long-range R&D goals of «conventional» photovoltaic technology can be pursued via theoretical work and computer modelling. New materials should be postulated and synthesized, ideally tailored by bandgap and crystal structure, to act as the constituents of multijunction solar cells. It is important to stimulate new theoretical studies (such as microstructure techniques) to provide a screening method to select promising candidates for new semiconductor materials. These materials should be capable of low-cost large-area deposition to give amorphous or polycrysylline thin films. New low-cost polymeric moisture-resistant encapsulating materials need to be developed. The goal should be low-cost (< 5 cents per kWh), high-efficiency (> 30%), long-life (> 30 years) photovoltaic modules manufactured to be easily incorporated into new houses or easily retrofitted to older houses.

For all photovoltaic systems, there is a need for all-solid-state, efficent, and reliable power conditioners (inverters) which incorporate power tracking for optimum output at a wide range of input DC power levels. Also, for stand-alone systems, low-cost totally reversible battery systems must be developed.

2. Biocompatible Ultra-Thin Solar Cells

There is another type of solar cell which deserves greater attention for long-range R&D. These cells would involve ultra-thin (< 100 nm) films, be of very low cost and would consist of biocompatible materials. These cells may degrade faster than conventional solar cells so they might need to be replaced after a few years. Due to their biocompatibility they could be produced in large quantities without adverse effects on the environment. These cells would be compatible, not only with the conversion of sunlight to electricity, but would also couple effectively into chemical energy storage and other interesting photochemical processes (e.g., information storage or biochemical reactions). With the rapid progress in the development of electrically conducting polymers, it is envisioned that polymer-based thin-film systems could be manufactured in large-area, consumer-friendly intergrated arrays for easy installation.

Characteristics of the Device

As a thin-film system, the device would have three basic layers: a cheap (probably plastic) substrate coated with a conducting layer (perhaps a wide-bandgap semiconductor film), an active layer containing the chromophores, and a protective transparent layer containing a conducting grid.

The active layer could be a mono- or multilayer system with organic or inorganic semiconductors.

Organic or Inorganic Semiconductor

This would have to be composed of materials with a very high absorption coefficient (> 90% absorption in < 100 nm), reasonable stability, low internal resistance, a high current quantum yield, and an absorption edge in the range 700–900 nm. No materials are now known which fulfill all of these criteria, but there is a reasonable possibility that such materials can be developed. Certain organic dyes (e.g. porphyrins, phthalocyanines) and certain inorganic materials (like FeS_2) do have the required absorption coefficients, but currently have far too high an internal resistance.

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Mono- and Multilayer Active Assemblies

These assemblies of inorganic or organic compounds, suitable for photo-induced charge separation, should meet the requirements as above, i.e., high absorptivity out to 700–900 nm, low internal resistance, and a high current quantum yield; in addition they should have a high degree of spacial organization. Sufficient optical absorption cannot be obtained by monolayers of either organic or inorganic compounds. Therefore the optical absorption cross-section has to be increased by either an optical antenna system or a multilayer system.

Fig. III1 gives an example of the use of an antenna system containing a series of sensitizers acting as excitation energy transfer agents, coupled to a charge-separating monolayer. This concept is based on the mechanism by which photosynthesis converts sunlight into chemical energy. Sunlight would be absorbed by a series of sensitizers covering the near-UV and visible solar spectrum. These sensitizers would be embedded in an electrically conducting layer (e.g., a conducting polymer) and would act as a light-gathering antenna in the sense that excitation energy would be transferred from one sensitizer to another until the excitation reaches a monolayer of a red-sensitive chromophore. Here the excited state of this chromophore would inject an electron (with high quantum yield) into the conduction band of a wide-bandgap, heavily-doped semiconductor, e.g., In-doped SnO_2 (this step has already been demonstrated). Electrons would flow from the monolayer chromophore to the base semiconductor, through an external load and finally back through a surface grid and the conducting sensitizer layer.

Indeed it may be possible to utilize this type of a monolayer-based cell in a multilayer configuration which could approach the very high efficiencies predicted for multijunction cells. The sensitized monolayer system simultaneously meets the requirements of high absorptivity, low internal resistance, and high degree of organization. Yield is governed by the photoelectrochemical properties of the monolayer.

An alternative approach to high optical absorptivity makes use of multilayer charge-transfer systems. Then it is necessary to design the assembly in such a way, that the internal resistance to electron flow is sufficiently low. Research should concentrate on defining the requirements to obtain such low resistance, specifically with respect to mutual orientation, distance, and degree of organization.

Multilayer charge-transfer systems may consist of stacks of one or more types of compound. A single layer should have internal, low-lying charge-transfer states. Mixed assemblies should consist of alternating layers of electron donors and acceptors at a distance and orientation favoring electron transport. By modifying the redox properties of subsequent layers, the assembly may act as an organic semiconductor, exhibiting photo-induced charge separation.

To obtain high current quantum yield, the ratio of the rate constants for charge separation and recombination should be as high as possible. Multilayer systems exhibiting multistep electron transport are expected to result in high current yield.

Technology should be further developed for the preparation of well-defined, highly organized thin-film assemblies by chemical synthesis, linking the photoactive compounds to electrically-conducting surfaces by modified vacuum deposition and deposition from solution.

The concepts presented above may also be applied to organized microheterogeneous systems (e.g., colloids and microemulsions) which are designed to couple the primary photochemical electron-transfer reactions to (bio)chemical processes. These could involve generation of energy-

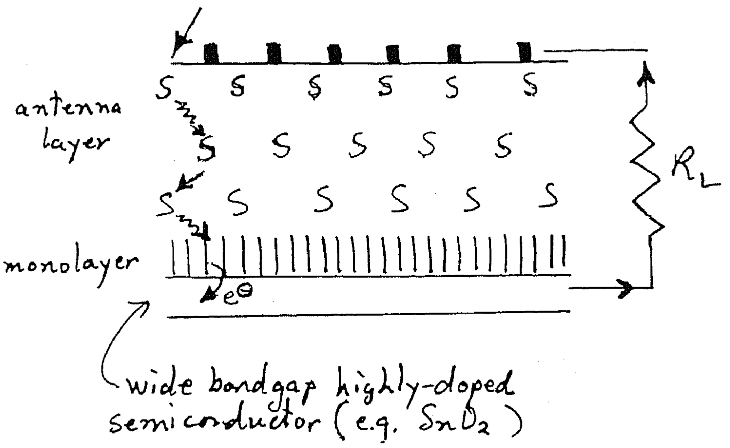

Fig. III1. An example of the use of an antenna system containing a series of sensitizers acting as excitation energy transfer agents, coupled to a charge-separating monolayer.

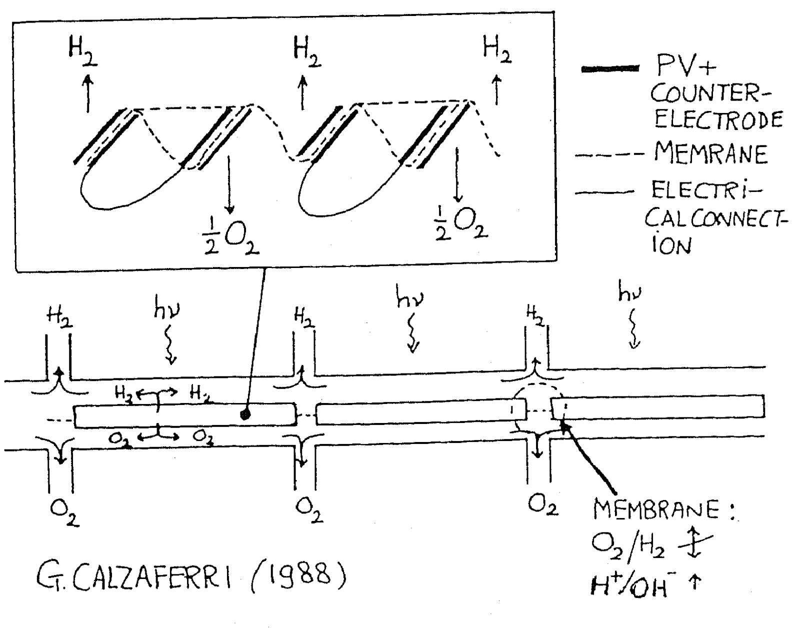

Fig. III2. A possible configuration with two electrodes.

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rich chemicals (fuels) and the use of fuel cells to extract the stored chemical energy as electrical energy. One such system could consist of plastic foils covered with organized microelectrodes for photoelectrolysis of water. In a «conventional» system photoelectrolysis of water can be achieved by applying three or four photovoltaic cells in series. In a similar manner, water photoelectrolysis can be achieved using organized microelectrodes. Fig. III2 illustrates a possible configuration with two electrodes.

The advantage of the organized microelectrode system over macroscopic electrodes in series is the absence of wiring. A disadvantage is that hydrogen has to be collected over a large area.

These thin-film concepts can be further applied to other photochemical processes such as the production of high-value chemicals (e.g. vitamin D).

Another possible application is the construction of devices integrating thin-films, which could include biological components (e.g., isolated reaction-center proteins from photosynthetic bacteria), into high-density optical information storage (it is estimated that as much as 50 gigabytes of information could be stored per cm^2) or ultrafast optical switches.

Adolf Goetzberger: Born 1928 in München, Federal Republic of Germany. Received his Dr. rer. nat. degree in physics from the Ludwig-Maximilians-Universität (LMU) München in 1955. Subsequently he joined Siemens in München where he worked on transistor development. From 1958 to 1963 he was with Shockley Transistor Laboratory, Palo Alto, California, collaborating with Nobel Laureate W. Shockley for four years and as manager for research and development for one year. In 1963 he joined Bell Telephone Laboratories in Murray Hill, NY where he initiated and participated in research related to silicon interfaces. In 1968 he returned to Germany to become head of the Fraunhofer-Institut für Angewandte Festkörperphysik in Freiburg i. Br., a nonprofit institution devoted to applied solid state physics. Work on solar energy which he started in 1976 led to the establishment in 1981 of the Fraunhofer-Institut für Solare Energiesysteme which he has been directing ever since. He is a professor at the University of Freiburg and is currently teaching courses on solar energy. His research interests include photovoltaic energy conversion, fluorescent concentrators, thermal solar energy conversion, and solar systems technology. Prof. Goetzberger is a fellow of the IEEE, a member of the American and German Physical Societies, the Electrochemical Society, and many other professional organizations. In 1983 he received the J. J. Ebers Award of the IEEE-Electron Devices Society for his work on device physics. He is advisor to the Commission of the European Communities and the German Ministry of Science and Technology on photovoltaic devices and materials.

3. Static Concentrators for Photovoltaic Systems

Adolf Goetzberger

A static (non-tracking) concentrator with a concentration ratio of 8–12 has been suggested. It consists of inexpensive refractive material, coupled to high-efficiency state-of-the-art solar cells. This concept promises to yield less-expensive, high-efficiency photovoltaic modules. The technologies needed are presently used in non-solar industry and would have to be adapted. It involves automatic handling of large numbers of small solar cells. These cells can be produced using standard integrated-circuit technology.

An R&D program should be developed including the following goals:

- Optimize optical modelling of concentrators.
- Identify or develop inexpensive, stable plastic materials with a high refractive index.
- Develop the most economical assembly technology.
- Develop suitable bifacial solar cells for two-sided concentrated illumination yielding an additional factor of two in concentration.

This same principle could be useful for photochemical processes in liquids.

Some problems may be expected to arise, such as combination of microelectronics manufacturing techniques with photovoltaic module production. A detailed description of this concept can be obtained [A. Goetzberger, *Proc. IEEE PV-Specialists Conf., Las Vegas, Sept. 1988*, in press].

Long-Range Impact on National or International Global Energy Systems

These ultra-thin solar cells would primarily have an application in domestic household electricity generation. This would favor the evolution of a more decentralized power generation system integrated with central power stations. Probably, as with conventional photovoltaic systems, many of the early applications would be in the Third World. The development of these types of solar cells would have little or no contribution to the greenhouse effect; however, the nature of the materials would have to be designed carefully so as not to cause a disposal problem.

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Photochemistry

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1. Novel Directions

1.1. Solar Energy Pumped Lasers (SEPL)

It is now possible, with solar energy concentrators, to supply a solar furnace with sufficient photons to heat it up to at least 1375 °C. With this kind of photon density, it is also possible to pump lasers. The lasers can then be used in the synthesis of expensive pure material by wavelength-selective destruction of small amounts of impurities in precious solids or in surface modification of highly technical devices by controlled photochemical deposition.

It is recommended that this kind of laser pumping be incorporated as part of a solar energy chemical factory (solar furnace). In such an arrangement, the laser pumping may use a narrow frequency band of the total solar energy spectrum, leaving the (broad band) rest of the concentrated solar energy to heat up the solar furnace. It is also possible to place the laser cavity in the focus of the concentrator when needed and remove it when it is not needed.

1.2. Proton Gradients and Proton Pumps

The two photosynthetic systems in nature are chlorophyll (green plant) and bacteriorhodopsin. The first one absorbs solar energy and pumps electrons while the second system uses solar energy to pump protons across its membrane. This creates proton gradients whose electric fields are used to convert ADP into ATP (the fuel of life). Interestingly enough, even the electron pump system of chlorophyll reduces the quinone, which is used in subsequent chemical reactions, to create proton gradients used for the making of ATP. Furthermore, bioenergy conversion in biological systems frequently involves the use of proton gradients in the conversion of energy into chemicals. In spite of this, most of the theoretical and experimental research efforts in solar energy have been spent to understand or develop energy converters using electron transfer reactions and only minor effort on proton transfer reactions. Of course if electric current is what is needed, electrons are more preferable due to their high mobilities. However, if the

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