

Third-Generation Photovoltaic Technology – The Potential for Low-Cost Solar Energy Conversion

For the Spring meeting in San Francisco this year, the ACS has chosen to concentrate on one of the most important challenges facing the world today — energy. On the basis of the theme “Chemistry for a Sustainable World”, symposia are planned for battery technology, fuel cells, and solar energy. Considering the fact that the amount of solar energy impinging the earth's surface in 1 h is equivalent to the amount of energy consumed by mankind in 1 year, we simply cannot ignore the opportunity that is presented by the use of solar energy. Solar energy is the ultimate renewable, zero-emission energy source, and it is abundant for most of the year in most parts of the world. In the United States, as in the rest of the world, solar energy generation, combined with wind and geothermal, represents a small fraction of the power generated from other sources such as coal, oil, and natural gas. However, it must be realized that one of the drawbacks to solar is that half of the earth is in darkness for a very large portion of the daily cycle. Consequently, solar must be combined with a means of energy storage in order for it to be practical.

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Solar energy technology, which is dominated by crystalline silicon, has not found widespread acceptance up to now due to the size, weight, and, for many potential customers, the aesthetics of these solar panels. However, perhaps the most frequently cited reason for this lack of widespread use is the cost of the solar panels themselves and the cost of installation, which represents approximately half of the total cost. Alternative materials, such as amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), which at the present time are not as efficient as crystalline silicon (5–15 versus 20% for the latter), are currently in various stages of development and commercialization. As a group, these materials are referred to as second-generation or thin-film technologies because they can be manufactured using roll-to-roll processes, which have the potential to make them significantly cheaper to manufacture than crystalline silicon. Lower manufacturing costs translate to lower electricity costs, which are estimated to be around \$1–2/Wp at high production volumes and efficiency (5–12%).

In the late 80s and early 90s, two new approaches to low-cost photovoltaics emerged. The first was a system based on sintered titania that is made sensitive to solar radiation by attaching a dye to its surface in analogy to dye-sensitized silver

halide emulsions used in traditional photography.¹ Because the titania sintering process must be done at temperatures in excess of 500 °C, flexible titanium or stainless steel substrates are used. The dye-sensitized titania cells are encapsulated with flexible plastic sheets to contain the liquid electrolyte and protect the cells from damage. The process can be manufactured in a continuous roll-to-roll operation, thus making it less expensive than crystalline silicon and in the range of the second-generation thin-film technologies. From a performance standpoint, the best laboratory cells exhibit efficiencies over 10%, with module efficiencies ranging from 3 to 5%. An example of a flexible organic photovoltaic panel is shown in Figure 1.

In this same time period, another thin-film technology, currently referred to as organic photovoltaics (OPV), was discovered.² As the name implies, this technology comprises carbon-based materials. The feature that differentiates OPV from all of the others is the roll-to-roll processes that are used to manufacture the cells and modules. These processes are typical of those used in the printing and coating industry in that solutions of the active materials, dissolved in organic solvents or water, are applied to a plastic sheet and dried producing a solid-state photovoltaic device.³ The maximum efficiency of cells is now approaching 8%; the best modules are in the 4–5% range. For a variety of reasons, not the least of which is the relatively simple, high-speed, large-scale manufacturing processes that are being developed, OPV is considered by many people in the field to offer the best chance of producing electricity at much less than a \$1/Wp.

A Perspective on Organic Photovoltaics (OPV) is presented in the article by Giridharagopal and Ginger⁴ from the University of Washington. In this paper, the authors center their discussion on the key aspect of the OPV cell, namely, the phase-separated, bicontinuous mixture of p-type and n-type charge carriers in the active layer. This layer is referred to as a bulk heterojunction (BHJ). The formation of the BHJ is kinetically controlled and is affected by the interactions in solution between the p-type polymer, the n-type fullerene, and the solvent, plus the process temperature and the evaporation rate of the solvent. Consequently, the researcher or engineer attempting to affect the bulk morphology, for example, the domain sizes of the p- and n-type carriers, which are essential for good performance, is faced with a very difficult task. The ability to characterize this layer is key to understanding the nature of the phase structure that generates high or low performance. The authors evaluate the utility of several characterization techniques and discuss the concepts and conclusions that have been obtained from each.

A brief review of progress toward “one-dimensional, nanostructured” materials for BHJ organic photovoltaic technology is given in the Perspective by the Kyoto University group.⁵

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Figure 1. A flexible organic photovoltaic panel is shown charging a storage battery. The panel can be conveniently rolled into the canister (bottom) for storage and transport. (Photo courtesy of R. Gaudiana).

The basic premise is that morphological control of this layer will aid light harvesting, charge transport, and photocurrent generation and will retard or eliminate bimolecular recombination. There are two approaches; the first deals with self-assembly of the donor and acceptor components of the BHJ layer. Successful attempts have been made to accomplish intermolecular association between the donor and acceptor

by means of liquid crystalline donor polymers, hydrogen bonding, and complexation between the donor and acceptor. The best result thus far exhibits IPCE of 60%. Unfortunately, most values are <20%. The second approach, for example, the 1D nanostructured electron-transporting layer, utilizes the concept of a gradient or what is commonly known as “vertical” phase separation. In these examples, inorganic semiconductors, such as TiO_2 or ZnO , in the form of columnar domains or fibrils or a layer with vertically aligned tunnels are grown off of the surface of a metal electrode. Growth of these structures has been accomplished successfully, but when a p-type charge carrier such as a donor polymer is added, the efficiency exhibited by the resulting cells is <2%. While most researchers in the field consider this approach to have great potential, it has not yet resulted in good performance.

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In conclusion, organic photovoltaics offer currently lightweight, low-cost portable battery charging, and when high-performance and long-term stability are achieved, this technology has the potential to become a major contributor to a renewable energy future. In order to realize this potential, we must understand the details of the working mechanisms upon which the technology depends from the macroscopic to the molecular level.

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