2-2-4. Dye-Sensitized Solar Cells

Overview

Dye-sensitized solar cells (DSSCs) generate electricity using a dye adsorbed onto an oxide semiconductor such as titanium dioxide. Since high efficiency was first achieved by Grätzel in 1991, DSSCs have been actively researched for practical applications, owing to their potential for low-cost fabrication via printing technologies and their strong performance in low-light conditions. Current research spans from fundamental photochemistry to novel principles utilizing intermolecular and spin-orbit interactions in dye molecules.

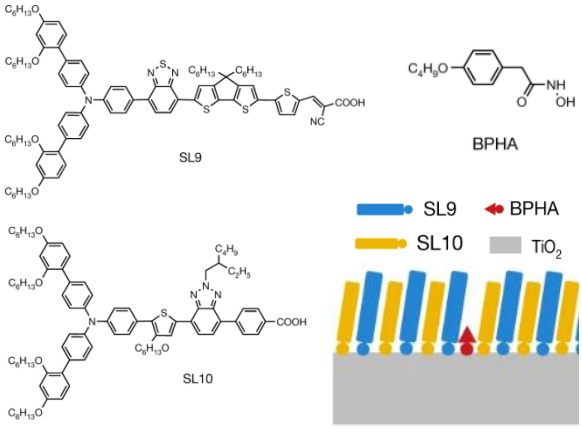

Figure 1. Conceptual diagram illustrating the dense and orderly arrangement of co-sensitizing dyes on a surface modified with a pre-treatment molecule.

Current Status and Frontiers

In Japan, a great number of researchers have been leaders in the field of dye-sensitized solar cells since the 1990s, with significant contributions in areas. For an overview of this field up to the mid-2000s, refer to section "2-2-2. Dye-Sensitized Solar Cells" in the Photochemistry Div Report described in Japanese. URL: https://division.csj.jp/div-report/02/0220202.pdf Research at the forefront of DSSCs focuses on enhancing key components, particularly the dye and the electrolyte. Dye development has progressed from improving the performance of single dyes to using multiple dyes ("co-sensitization") and capturing previously unused infrared light. Meanwhile, to improve stability and voltage, solid-state electrolytes and new redox materials such as copper complexes are replacing traditional iodine-based liquids.

A major breakthrough involves pre-treating the titanium dioxide surface with compounds such as BPHA. This method creates a highly organized dye layer, which suppresses energy loss and has led to a record conversion efficiency of 15.2%, with efficiencies exceeding 30% reported under indoor lighting (Grätzel et al.). Additionally, research has been reported that presents a new academic concept based on photochemical reactions for the utilization of infrared light, which has been previously unused in DSSCs. In principle, solar cells have a lower energy limit for the light they can absorb, meaning that near-infrared light has traditionally been unutilized. For instance, in well-known, high-efficiency ruthenium complex dyes, the process begins with a spin-allowed $S_0 \rightarrow S_1$

absorption, followed by intersystem crossing to the T_1 state. It is from this T_1 state that an electron is injected into the titanium dioxide. Therefore, if the energetically lower, forbidden $S_0 \rightarrow T_1$ transition could be realized, it would be possible to utilize even longer-wavelength infrared light. Indeed, an incident photon-to-current conversion efficiency (IPCE) spectrum corresponding to this $S_0 \rightarrow T_1$ absorption, rising from around 1050 nm, has been reported for a ruthenium complex dye with a phosphine ligand (Kinoshita, Segawa et al.).

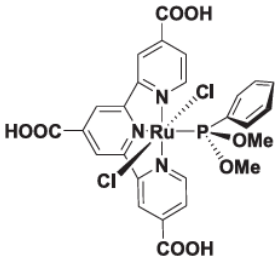

Figure 2. Example of a phosphine-ligated Ru complex dye exhibiting S-T absorption.

Another method being considered to utilize long-wavelength light is triplet-triplet annihilation (TTA). This technique involves co-adsorbing a platinum porphyrin complex and diphenylanthracene onto titanium dioxide. By controlling the distance between the complex and the titanium dioxide film, TTA is induced, leading to electron injection from the anthracene (Nagata et al.).

While achieving high efficiency with these methods presents various challenges, such molecular approaches are significant for fundamental photochemical research, as they help elucidate underlying reaction mechanisms.

Separately, following reports of open-circuit voltages exceeding 1.1 V with redox electrolytes replacing iodine (Hagfeldt et al.), there has been growing interest in applying high-voltage DSSCs as standalone power sources for IoT devices and sensors.

References

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Future Perspectives and Directions

Establishing long-term stability of over 20 years to withstand outdoor use.

Establishing a market for IoT power sources, with full-scale societal implementation in building materials, wearable devices, and more.

Achieving a conversion efficiency in the 20% range, approaching the theoretical limit, by integrating advanced technologies such as photon upconversion.

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