Dye-Sensitized Solar Cell for Energy Harvesting Applications

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A dye-sensitized solar cell (DSC) has unique properties that the cell performance does not readily decrease even at higher incident light angles compared with a Si solar cell and dose not decrease or rather increases under low light conditions. Fujikura is developing new applications of DSC by taking advantages of these properties to the field of "Energy Harvesting" where rapid growth of market has started recently. The results of our outdoor operation tests showed that a DSC generates 1.4 times larger power than a polycrystalline Si solar cell that has the same rated output, when a DSC module is placed on a north wall where the sun light dose not arrive directly. The DSC specially developed for indoor use has twice larger generation performance than amorphous Si solar cells. In this paper we will introduce these technologies of DSC.

1. Introduction

Photovoltaics is expected to be a key technology to future power generation to lead a low-carbon society. Several novel solar cells are being developed in addition to presently commercialized ones, for example, crystalline Si solar cells using bulk Si wafer, thin Si solar cells such as a-Si solar cells, compound semiconductor solar cells like a $CuInGaSe_2$ (CIGS) cell, a CdTe cell. Dye-sensitized solar cells (DSC) have been actively developed as one of the candidates of novel environment friendly photovoltaic technologies since the first report by Grätzel in 1991 [1]. A DSC is fabricated by a simple and low energy consumption process based on a screen printing process without toxic materials so that it has the potential to become excellent clean energy sources of next generation. We found unique properties of DSC attributed to its peculiar device structure and generation mechanism different from conventional solar cells. The device is expected to be utilized in new fields such as energy harvesting, which is promised to grow notably in near future.

2. About Dye-sensitized Solar Cell

Figure 1 shows a typical structure of DSC. Dye molecules as a photo-sensitizer adsorbed on TiO_2 nanoparticles of mesoporous layer are excited by light. The excited electrons are injected to the conduction band of TiO_2 and transferred to out of the cell. The excited dye molecule is regenerated by redox system, which is typically iodide/tri-iodide (I^-/I_3^-) dissolved in organic solvents. The oxidized redox species themselves are regenerated at the counter-electrode by electrons passed through the outer circuit. The cell operates by these charge-transfer processes.

In 2011, the highest value of the authorized energy conversion efficiency of DSC was updated after all these years. It was 11.4% of an about 5 × 5 mm^2 mini-cell reported by NIMS group [2]. The highest authorized energy conversion efficiency is 11.4% for an about 5 × 5 mm^2 mini-cell, which was reported by NIMS group in 2011. Recently, DSC development is moving toward the engineering research stage focusing on a practical application. Fundamental research and development on materials such as a novel dye and electrolyte are making steady progress in energy conversion efficiency [3], and in parallel, engineering research and development of designing large-sized modules and verifying long-term operation is also actively being conducted [4]. A new project of NEDO started in 2012 and is attracting attention of many researchers and

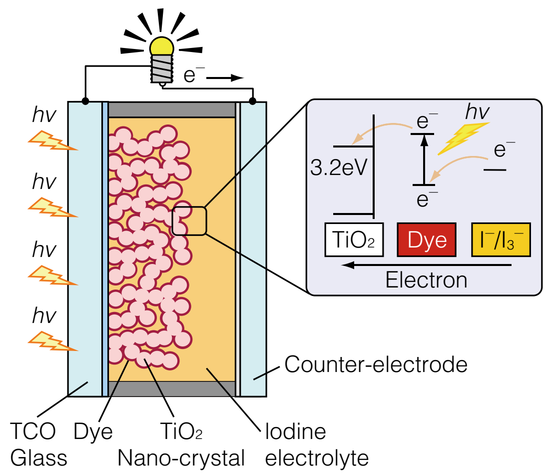

Fig. 1. Typical structure of a dye-sensitized solar cell.

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Abbreviations, Acronyms, and Terms.

TCO—Transparent conductive oxides

Energy conversion efficiency—Energy conversion efficiency (%)=100 × (Generated energy of a solar cell / Energy of incident light)

Sensor node—Devices composed of sensors, transmission units, power units.

METPV—Meteorological Test data for Photovoltaic system. It is a meteorological database of domestic 150 spots created by Japan Weather Association as a result of contract research of NEDO.

Rated output—Generation output measured under the conditions of 25°C (surface temperature) and 1 sun (standard condition). The output is defined by JIS standard.

N719, N749—Typical Ru complex dye as a sensitizer of DSC. N719 shows wine-red color and N749 shows dark green (black-like) color so that N719 and N749 are also known as "Red dye" and "Black dye" respectively.

Leak current—Phenomenon caused by recombination of electrons and holes (electrolytes), where photoexcited electrons are lost before working in outer-circuit. It causes decrease in energy conversion efficiency of DSC.

companies as the first nation-led field test project of DSC and organic thin-film solar cells. Fujikura is conducting the field test project while accelerating the DSC development. We aim to apply our DSC technologies to unique fields by taking advantages of the DSC characteristics clarified by our previous research. We focus on applications such as sensor nodes and power supplies for outdoor/indoor use in energy harvesting fields, which are expected as a novel energy utilization technology. In this paper, our DSC modules for both outdoor and indoor uses are introduced.

3. Introduction of the Technology

3-1 Dye-sensitized Solar Cells for Outdoor Use

Improvement in long-term stability of operation under the sunlight is one of the fundamental tasks for the development of outdoor use DSC. The durability of DSC is influenced by various factors, but preventing evaporation of electrolyte components including iodine is significantly important as well as blocking moisture intrusion into the cell. We developed our original sealing technologies and applied them to our DSC submodules to complete these technical tasks. Several endurance tests based on IEC-61646 standard were carried out, and the results showed that the DSC could pass tough endurance tests such as a 85 · 85%RH × 1000 h heat and humidity exposure tests for the first time in the world [5].

A DSC has a characteristic of coming under relatively small light exposure conditions compared to other kinds of solar cells. Figure 2 and 3 respectively show the relationship between incident light intensity and energy conversion efficiency, and between incident light angle and energy conversion efficiency. The performance of DSC does not decrease so much under higher incident angles of light and dose not decrease or rather increases under low light conditions. These characters suggest that a DSC has advantages in conditions of limited light such as in mornings, evenings, and setting on building walls, or significant weak light such as in cloudy and rainy days. In fact, our outdoor

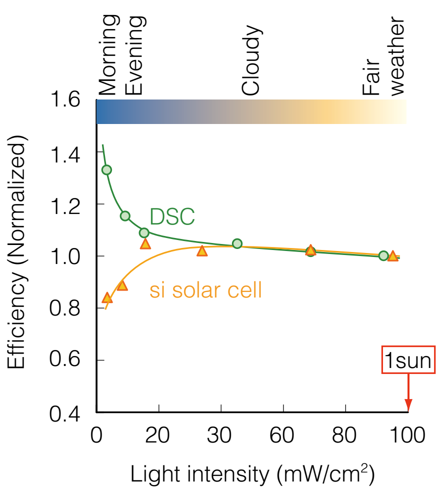

Fig. 2. Relationship between incident light intensity and energy conversion efficiency.

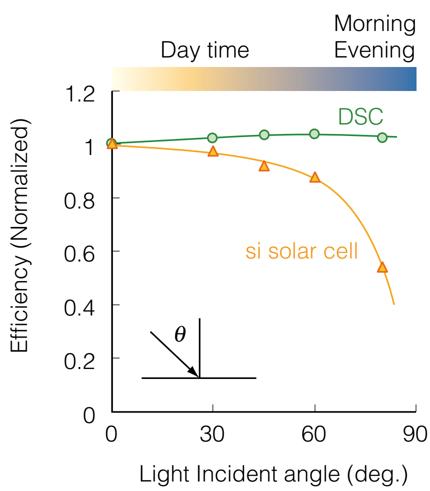

Fig. 3. Relationship between incident light angle and energy conversion efficiency.

Fig. 4. Outdoor operation test of DSC module panels.

operation tests of DSC modules (Fig. 4) showed data supportive of this prediction. Yearly generation amounts of DSC were estimated based on the outdoor operation tests by using a meteorological database, METPV. The results showed that a DSC generates 1.2 times higher power than a polycrystalline Si solar cell with the same rated output, when the DSC was placed on a south side of 30° slope setting, and specifically, 1.4 times higher power when placed on a north wall where the sun light does not arrive directly on the cell modules [6]. So far, the performance of the DSC under a fine solar irradiation condition has not reached the power generation performance of bulk crystalline Si solar cell. The results, however, revealed the stable and certain operation of the DCS under very low-light irradiation environments or unfavorable installation conditions for instance, the setting on the wall as described above due to its unique properties. So, we expect that a DSC operates effectively in applications like stand-alone power supplies, which are often installed in unfavorable light irradiation environments as its first commercial application.

3-2 Dye-sensitized Solar Cells for indoor Use

About half portion of sunlight spectrum belongs to the infrared region. The edge of light absorbance for crystalline Si solar cells or CIGS solar cells is over 1000 nm. On the other hand, that of a DSC is about 775 nm for N719, red dye, and about 900 nm for N749, black dye, which has a wider light absorption range compared to other typical dyes for DSC. Now, research and development of new dyes, which can convert irradiated lights with a longer wavelength to electric energy, and novel device construction is actively being conducted to increase energy conversion efficiency of DSCs [7].

In contrast, as most spectra of lights for indoor use including fluorescent lights and LED lights extend in visible light range, the light absorption range of a dye for DSC, N719, for instance, is suitable for such lights. In addition to this, given the fact that a DSC is capable of effectively generating power in low-light conditions, as mentioned above, it has advantages as a power generator for indoor use. Although the amount of energy obtained from indoor lights is very small compared to the sunlight, indoor power generation by DSC seems to be one of the best candidates to utilize limited energy in a room effectively such as energy harvesting applications mentioned below. Fujikura have developed a high performance DSC for indoor use in parallel with one for outdoor use (Fig. 5). We incorporated our proprietary technologies for matching spectral sensitivity of a device with that of illuminant, designing electrode conformation, and preparing electrolyte to decrease leak current drastically. As a result, our DSC specifically developed for indoor light achieved high energy conversion efficiency of over 20% under 1000 lux indoor light. It was about two times larger generation than that of amorphous Si solar cells, which are generally used indoors and have energy conversion efficiency of 11 − 12% under the same condition. In addition to use in bright environment like an ordinary office, our DSC operates with excellent performance in dim environment like a warehouse where it is difficult for conventional solar cells to operate with stability.

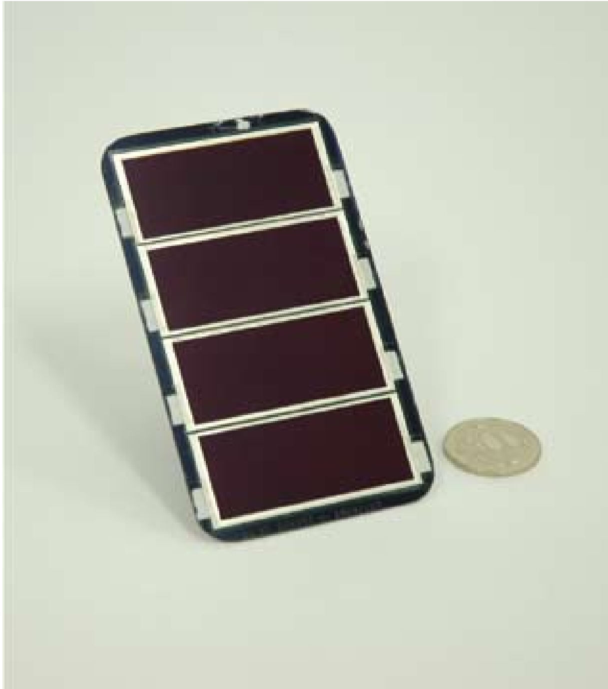

Fig. 5. A DSC module of four cells connected in series for indoor use.

3-3 Application of DSC to the energy harvesting technology

Recently, energy harvesting technologies have attracted attention [8]. They aim to utilize small amount of energy in our living environment that have never been used effectively following reductions in energy consumption of IC or transmitter to operate sensors and remote controls. There are various energy sources such as light, heat, vibration and radio wave for energy

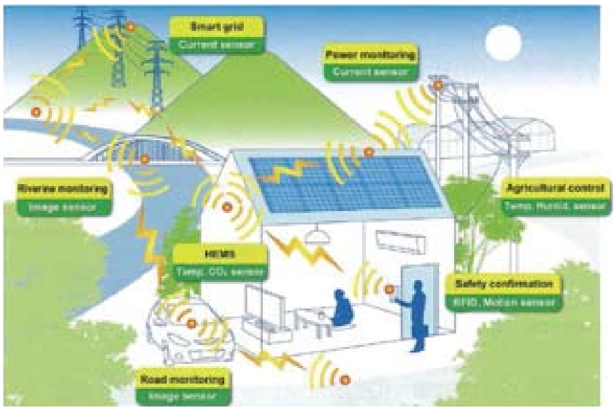

Fig. 6. Application of DSC in energy harvesting fields.

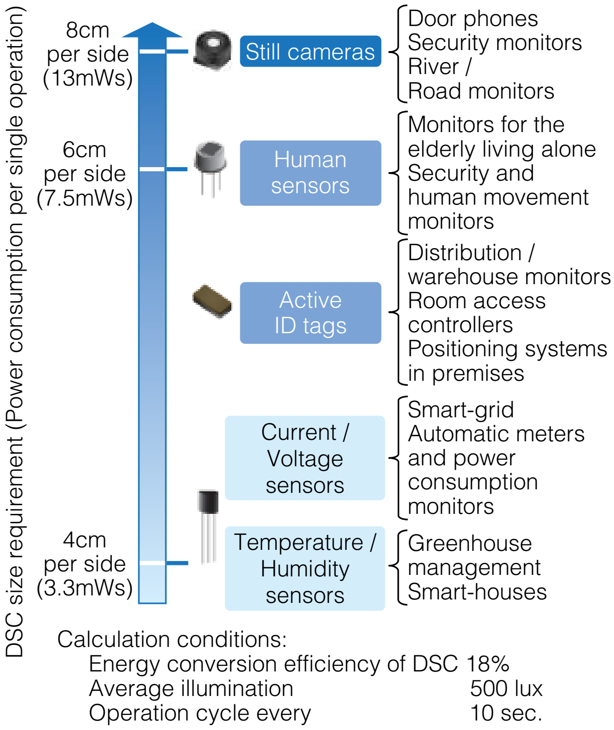

Fig. 7. Power consumptions of various sensor devices and required size of indoor use type DSC for their device operations.

harvesting but light seems to be suitable because its energy density is relatively large among other sources and easily available. We think a DSC must be effectively used in the energy harvesting field because it is capable of operating under very low light irradiation and is free of placement limitation as mentioned in the previous section (Fig. 6). A power supply for various sensors is a candidate for the application of DSC for energy harvesting use. In near future, while detecting and managing more information will be needed, being released from the labor work of battery change and complex electrical wiring for many sensor nodes will become an important technological task. Energy harvesting technology can be utilized indoors and outdoors. The indoor uses include information management in a smart-house or a large warehouse. The

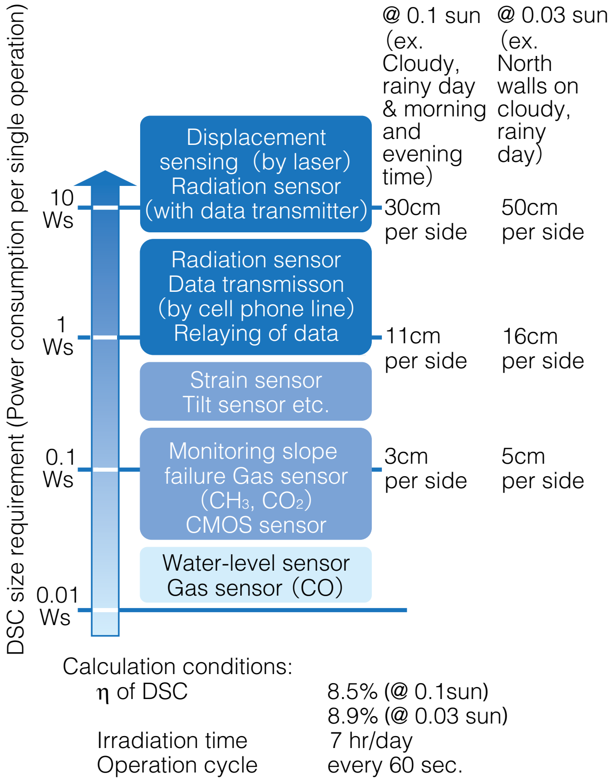

Fig. 8. Power consumptions of various sensor devices and required size of outdoor use type DSC for their device operations.

outdoor uses include real-time monitoring of data such as nuclear radiation, metrological data, road or bridge conditions at many points, which are required especially after the great east Japan earthquake. Figure 7 and 8 show power consumptions of various sensor devices and required sizes of DSCs for both indoor and outdoor. Even if available amount of light irradiance and installation conditions are limited, DSC will be work as a power supply of various kinds of sensor nodes in both indoor and outdoor. Demand for these applications will increase more in future, and our DSC will meet the demand and promise to assist comfortable and environment friendly life style.

4. Conclusion

A DSC operates with excellent performance under the conditions of very low light irradiation and large light incident angle where conventional solar cells can not operate with their best performance. These characteristics will enable various applications of DSC as useful power sources in the energy harvesting field. Fujikura aims to commercialize DSC as early as possible and contribute to future life style which will require both comfort and care for the environment at the same time.

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