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Increasing the Efficiency of Solar Cells by Combining Silicon- and Dye Sensitized Devices

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Abstract. This paper presents new integration techniques to combine silicon- and dye sensitized solar cells (DSSCs).

The idea of this work is to install DSSCs on the back side of silicon solar cell panels to make use of the reflected radiation from the ground or from solar cells arranged behind.

It has been shown that the architecture of the combined solar cells can be designed as monolithic structure by depositing the DSSC layers one after the other on the back side of Si-cells or as hybrid structure by combining Si-cells with foil-DSSCs. To enhance the current efficiency the different kinds of cells were connected in parallel. The TiO_2 nano particles, dissolved in dispersion, were coated on foil- or glass substrates. Here, it was possible to enhance the efficiency of dye sensitized solar cells by treating the semiconducting layer with pulsed UV radiation. As a result of the UV light treatment the short circuit current has more than tripled. Nevertheless, the cells maintain their low-cost characteristics, because synthetic dyes have not been used to coloured the nano particles. Additionally, the DSSCs were connected in series. Thus, it was possible to adapt the voltage of the DSSC to the voltage of the Si-cells.

Key words

Silicon Solar Cells, Dye Sensitized Solar Cells, Tandem Solar Cells, Renewable Energy, Performance Improvement

1. Introduction

Silicon solar cells are often assembled into arrays or solar panels. In solar parks or on flat roofs the solar panels are mounted at a defined angle to capture as much of the sun radiation as possible [1]. The reflected radiation from the ground or from solar cells arranged behind cannot be used. Here, further solar cells installed on the back side of the solar panels would be necessary. Due to the several advantages of dye sensitized solar cells (DSSCs) like low cost-, short time fabrication, and diffuse light compatibility, DSSCs are suitable to make use of the reflected light that reaches the back side of solar panels.

Hence, this paper discusses several possibilities to combine silicon solar cells and DSSCs. The aims of the combination were twofold: to deposit the DSSC layers one after the other on the back side of Si-cells and the hybrid interconnection of Si-cells and flexible foil-DSSCs. In any case the cells were connected in parallel to improve the current efficiency.

Unfortunately, the use of low-cost materials like natural dyes reduces the power output of DSSCs [2],[3]. Therefore this paper presents some intelligent solutions to improve the energy output by maintaining the low-cost characteristics of these cells. One possibility to increase the voltage is to connect DSSCs in series [4],[5]. Accordingly, the different layers were deposited and structured to build up DSSCs connected in series on the back side of silicon solar cells. Here, the charge transfer strongly depends on the choice of materials.

One possibility to enhance the current is a thermal treatment to sinter the nano particle semiconducting layer of the DSSC. Due to the high temperature which must be applied to get a reasonable sinter effect, thermal sintering is not applicable by using temperature-sensitive ITO foil substrates. Here, experiments show that direct UV radiation of the TiO_2 nano particles improves the film quality. The UV light does not affect the substrate due to its transparency. According to this, ultraviolet light treatment is an effective way to interconnect the nano particles and to improve the electrical connectivity between the particles and the ITO electrodes. In this case, the radiation power of the light source and the exposure time strongly influence the current efficiency.

This method enables to increase the output of DSSCs on foil substrate by a factor of 3.

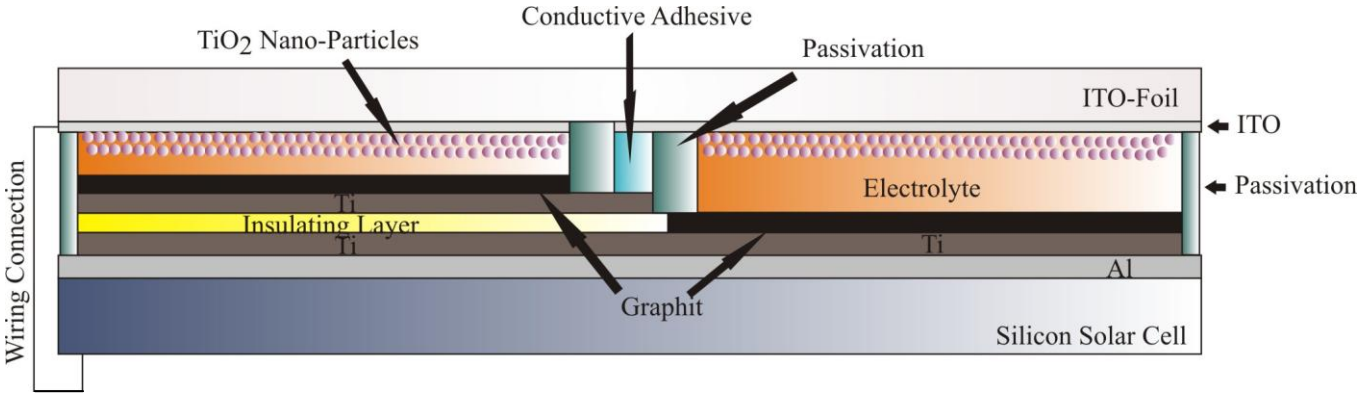

Fig. 1. Layer structure of the DSSC series connection on the back side of a silicon solar cell

2. Experimental details

To enhance the current efficiency the different kinds of cells were connected in parallel. The connection was realized by using a wiring connection and a conductive adhesive. Initially, the DSSC layers were deposited and structured on the back side of a silicon solar cell. Here, it is important to adapt the voltage of the DSSC to the voltage of the Si-cell. This was achieved by connecting the DSSCs in series.

Thereafter, typical flexible DSSCs on foil substrate were analysed, optimised and connected with a silicon solar cell. Thus, it was possible to compare a monolithic structure with a hybrid interconnection of DSSCs and Si-cells

A. Monolithic structure

Before depositing the DSSC layers, a titanium layer was sputtered on the Al back side contact of a 100 mm Si-cell. By this, the Al back side of the Si-cell is protected from the corrosive effects of the DSSC electrolyte. Later, the two different solar cells use this layer as common positive pole.

Afterwards, a graphite layer was sprayed on the titanium surface. Graphite is an essential catalyst and enhances the charge exchange inside the DSSC [6],[7].

The major perceived problem of DSSCs is the long term stability [8],[9]. The heat of the sun causes the evaporation of the electrolyte. Therefore, a passivation is needed. Here, silicon paste is well suitable as passivation layer in principle. The advantages of silicon paste are the good workability, the low costs and the flexibility of the material. The paste was deposited and structured round about the graphite layer by using a syringe.

After this, FTO glass substrates or ITO foil substrates were deposited with TiO_2 nano particles dissolved in dispersion. Here, the doctor blade technique was used. Glass substrates are more expensive than foil substrates and don´t allow the same flexible adaption to different Si-cells. Though, DSSCs with glass electrodes achieve a higher power. This is due to the reduced sheet resistivity of the FTO surface and the possibility to sinter the nano particle semiconducting layer by 450 degrees. Because of the advantages of both materials this paper compares the results of DSSCs with glass and foil substrates.

Thereafter, the nano particles were coloured by using hibiscus extract. Synthetic dyes have not been used to coloured the nano particles. Thus, the DSSCs can retain their low-cost, sustainable character.

Then, the coloured substrates were placed on the prepared Si-cell. The passivation of silicon paste forms the glue to connect the Si-cell and the glass- or foil substrate. The substrates and the top side contact of the Si-cell form the negative pole. The electrical connection is obtained by using a wiring connection and a conductive adhesive.

Before starting the measurements of the short circuit current and open circuit voltage of the solar cells a liquid electrolyte was inserted by using a syringe. Subsequently, the DSSC is activated and increases the efficiency of the silicon solar cell.

Table I shows the results of the measurement that taken on a sunny day (132 000 lux). Clearly, the significant difference between glass and foil substrates is the short circuit current I_{SC}. The I_{SC} of the DSSC with foil substrate is approximately five times smaller than the I_{SC} of the DSSC with glass substrate.

One of the main reasons is that thermal sintering is not applicable by using temperature-sensitive ITO foil substrates. Fortunately, experiments show that pulsed UV radiation of the TiO_2 nano particles improves the film quality like thermal sintering. The pulsation is required to reduce the high temperature radiation of the UV lamp to the foil. This method enables to increase the short circuit current of DSSCs with foil substrate by a factor of 3.6 (Table I).

The treatment method and the supporting effect on the TiO_2 nano particles are further examined below. Obviously, UV radiation has a positive effect on the semiconducting layer. At the first glance, the visible surface of the nano particles changes the colour from white to light blue. However, the use of an electron

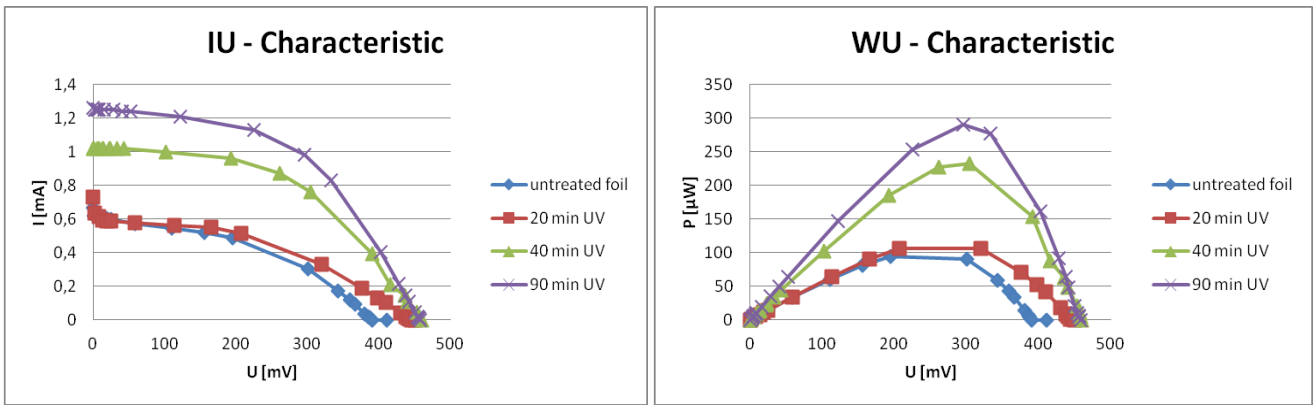

Fig. 2. IU-characteristic and WU-characteristic curves of DSSCs with foil substrates (Active Surface 66 cm²; Illuminance 132 000 lux)

microscope enables to get a detail view of the surface characteristics. Figure 3 shows that, in general, the surface gets rougher and can thus absorb more dye. Consequently, the nano particles are able to absorb more free charge carriers. For this reason, the current efficiency is increased significantly.

Furthermore, it can be reasonable expected, that the UV light treatment also improves the quality of the barrier layer between the nano particles and the ITO surface. This reduces the internal resistance of the DSSC and increases the charge transfer.

In order to be able to make statement on the impact of different exposure times, TiO_2 nano particles were treated for 20 min, 40 min and 90 min by using a 3000 W UV lamp. The specified exposure times also include the intervals between the light pulses. Figure 2 shows the IU-characteristic and the power characteristic curves of DSSCs with foil substrates for different exposure times. It is recalled, that the DSSCs are connected to the back side contact of a 100 mm Si-cell. The values were measured by using a 250 W halogen lamp (21400 lux, Distance: 37 cm) and an active surface of 66 cm². Nevertheless, the results illustrate the power enhancement of the cells. The enhancement of the short circuit current and open circuit voltage is shown in Table II. As a result of the UV light treatment the short circuit current has doubled and the MPP-power has tripled. Certainly, in future, the output of the DSSC could be further enhanced by extension of the exposure time.

Due to the proposed installation of the DSSCs on the shady back side of solar panels, the open circuit voltage will be lower than that indicated in Table I.

Here, it is important to adapt the voltage of the DSSC to the voltage of the Si-cell by connecting several DSSCs in series.

To build up a DSSC series connection on the back side of a silicon solar cell the following process steps were used. Starting with a 100 mm Si-cell, a titanium layer was sputtering on the Al back side contact. In the next step, the first graphite layer and an insulating layer were deposited and structured by shadow masks. As insulating material silicon dioxide, photoresist and glue were tested. Compared to other materials glue was best suited for this purpose. Here, the doctor blade technique was used.

Thereafter, the insulating layer was sputtered with titanium and coated with graphite. In the middle of the surface a conductive adhesive was coated by using a doctor blade. The adhesive connects the two DSSCs in series. Next to the adhesive and around the cell the passivation was coated (silicone paste). Finally, a structured ITO foil was deposited with a nano particle semiconducting layer. The nano particles were treated with pulsed UV radiation for 90 minutes and were coloured with the natural dye. After all that, the ITO foil was placed on the prepared Si-cell. The liquid electrolyte was inserted by a syringe. Figure 1 shows the layer structure of the DSSC series connection on the back side contact of a silicon solar cell. The values of the short circuit current and open circuit voltage of the resulting DSSC are contained in Table I. Predictably, the open circuit voltage has nearly doubled. The short circuit current is smaller now, because two single DSSCs have to share the same active surface.

Table I. – Short Circuit Current and Open Circuit Voltage of the solar cells

Active Surface: 66 cm² Distance: 37 cm	Illuminance:	132 000 lux (sunny day)

	I_{SC}	U_{OC}
DSSC with glass substrate	5.5 mA	489 mV
DSSC with foil substrate	1.1 mA	480 mV
DSSC with foil substrate and 90 min UV treatment	4 mA	525 mV
Two DSSCs on foil substrate connected in series	1.53 mA	1180 mV
Si-Cell	430 mA	530 mV

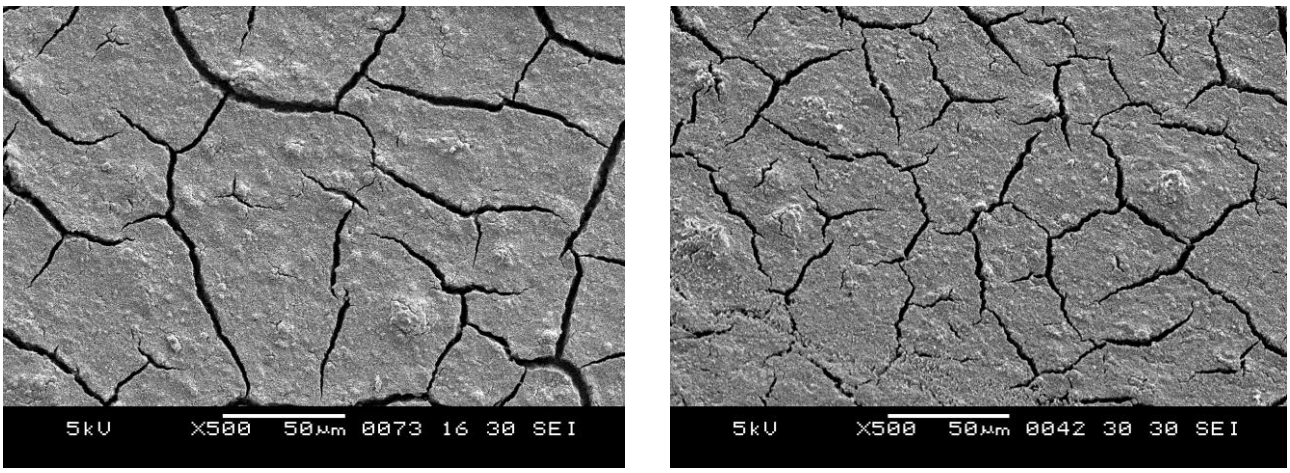

Fig. 3. REM photograhps of the semiconducting layer before (left) and after (right) the pulsed UV radiation

Table II. – Short Circuit Current and Open Circuit Voltage of the foil-DSSC connected to the Si-cell back side contact

Active Surface: 66 cm² Distance: 37 cm	Illuminance:	21 400 lux (halogen lamp)

	I_{SC}	U_{OC}
Untreated Foil	0.66 mA	411 mV
20 min UV	0.73 mA	450 mV
40 min UV	1.02 mA	467 mV
90 min UV	1.26 mA	466 mV

B. Hybrid structure

The hybrid structure consists of a silicon solar cell and an optimised DSSC on foil substrate. Similarly, the current efficiency was enhanced by connecting the two kinds of solar cells in parallel. The electrical connections are realized by wires and conductive adhesive. Figure 4 schematically shows the structure of a DSSC on foil substrate.

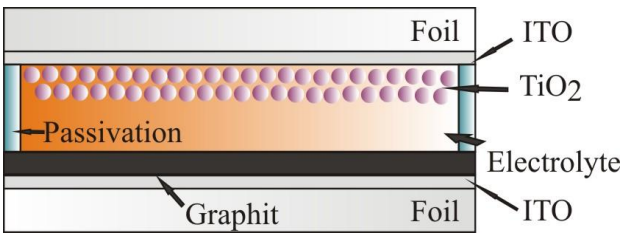

Fig. 4. Layer structure of the DSSC on foil substrate

At first, ITO foils were adapted to the used silicon solar cells regarding shape and size. One foil electrode forms the negative pole and was coated with TiO_2 nano particles. Before the semiconducting layer was coloured the foil was treated with pulsed UV light to improve the film quality of the semiconducting layer.

Compared to the monolithic structure, the DSSC counter electrode of the hybrid structure consists of an ITO foil. The counter electrode was coated with graphite. Between the foils the passivation layer was deposited. To activate the foil-DSSC the liquid electrolyte was inserted by using a syringe.

The enhancement of the short circuit current and the open circuit voltage of DSSCs on foil substrate by using pulsed UV radiation is shown in Table III. In comparison to the untreated foil-DSSC the current of the improved foil-DSSC has more than tripled. The open circuit voltage has also increased. Though, the current of the foil-DSSCs are smaller than the current of the DSSCs with foil substrate connected to the Si-cell back side contact. This is due to the reduced sheet resistivity of the ITO surface. In other words, the sputtered titanium layer absorbs more free charge carriers than ITO.

However, even in this case, the use of pulsed UV radiation enables to combine silicon solar cells with foil-DSSCs to increase the efficiency.

Hence, all benefits of the hybrid structure with foil-DSSCs can be utilized. The foils can be adapted to the shape of any silicon solar cell panels. Existing solar panels can be easy retrofitted. The foil-DSSCs are easy to process, lightweight, space saving and comfortable to transport.

In general, all materials are cheap and environment-friendly. Indeed, due to the continued shortage of ITO, the prices of this material will raise.

Therefore, an alternative material for the electrodes will need to be sought. One possibility could be to sputter a thin Ti layer on top of the foil substrate. Here, the Ti layer thickness shall not exceed 9 nm. Up to a thickness of 9 nm the light transmission decreases strongly.

Furthermore, synthetic dyes like ruthenium complexes would increase the power output of the DSSCs [10]. But the costs of the solar cells would definitely increase, too. Additionally, the environment compatibility decrease, the

handling and the process would be more difficult and the cells would be classified as being a hazard to health.

Table III. – Short Circuit Current and Open Circuit Voltage of foil-DSSCs

Active Surface: 66 cm² Distance: 37 cm	Illuminance:	21 400 lux (halogen lamp)
	I_{SC}	U_{OC}
Untreated Foil	0.33 mA	340 mV
90 min UV	1.11 mA	470 mV

3. Further Information

Questions may be addressed to:

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4. Conclusion

The experiments demonstrated the potential of dye sensitized solar cells. They not only offer several advantages like low cost- and short time fabrication, and diffuse light compatibility. Especially, foil-DSSCs can be a significant complement to conventional silicon solar cells. The foils can be adapted to the shape of any silicon solar cell panel. It is possible to build up hybrid or monolithic structures. The power output of foil-DSSCs can be increased by using pulsed UV radiation. This will maintain the low-cost, sustainable character of the DSSCs. Further, series connections help to adapt the voltage of the DSSCs to the voltage of the Si-cells.

As insulating layer silicon paste has been used. Despite good results, no passivation material is reliable for long periods. Here, a refillable system for electrolyte fluids should be installed.

In spite of the optimisations, compared with Si-Cell the efficiency of DSSCs is much smaller. Nevertheless, DSSCs offer a cost effective opportunity to make use of the reflected light that reaches the back side of solar panels.

In summary, it can therefore be said, that the combination of silicon- and dye sensitized devices can increase the efficiency of solar cells.

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