Development of Lower Cost Monolithic Dye-Sensitized Solar Cell with Carbon Counter-Electrode

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Abstract: Dye-sensitized solar cells (DSSCs) were developed as low-cost and environmentally friendly alternatives to other types of solar cells. However, due to efficiency and stability shortcomings, and also because of the cost reductions in crystalline Si cells, DSSCs are not yet commercially successful. Several parameters have to be improved, one of which is the cost that should be reduced further. There are two ideas to achieve this: the platinum electrode can be substituted by a cheaper carbon electrode, and the sandwich structure of the cells, with two glass substrates with a transparent conducting oxide (TCO) layer on them, can be changed to a monolithic structure, in which only one TCO-coated glass substrate is used. In the present project the performance of such monolithic cells with carbon counter-electrode is compared to the performance of cells with sandwich structure that are otherwise identically constructed. The performance assessment was done by means of an I-V curve measurement. The main result is that monolithic cells have a lower efficiency. The data indicate that the internal serial resistance of the monolithic cells was higher than in the sandwich cells. In a further step, three monolithic cells were interconnected in series in a submodule, and the performance of this submodule was assessed. The result indicates that the serial resistance of the three cells that were interconnected in the submodule, including the contacts, was lower than three times the serial resistance of the individual cells including the contacts. This shows that there is a potential for a more efficient usage of monolithic cells by means of a module design that allows for lower resistances in the interconnection of the cells within the module as well as in the module contacts. This should be pursued in further research, as well as the reduction of the internal resistance of the monolithic cells.

Keywords: carbon counter-electrode, dye-sensitized solar cell, module, monolithic, scale-up.

1. Introduction

Solar energy as the largest source of renewable energy comes in the form of sunlight that is radiated by the sun. The energy of the sun that is irradiated across the earth ranges from 800 to 2600 kWh/m^2 per year, as it is depicted in Figure 1. In principle, if solar energy is utilized on a large scale, the energy problems can be solved worldwide.

The energy of the sun can be harnessed by using photovoltaic (PV) technology. Since the photovoltaic effect was discovered, the PV technology has been developed to make power cleaner, more environmentally friendly, and more reliable compared to fossil resource based energy (Chodos, 2009). The first generation of PV technology was dominated by crystalline silicon solar cells. This was followed by thin film solar cells as the second generation. These kinds of solar cell have several drawbacks, such as the high cost to purify the required silicon material for silicon-based solar cell, the fact that some of the thin film solar cells contain elements that are toxic, and the scarcity of some of the materials for thin film solar cells (Chung *et al.*, 2012). To overcome the disadvantages of the former generations of solar cells, a low-cost and environmentally friendly dye-sensitized solar cell (DSSC) was invented by Michael Grätzel. These cells absorb radiation by means of a dye in a similar way as chlorophyll absorbs light in plants (Grätzel, 2003). Another advantage of a DSSC, aside its lower manufacturing costs compared to silicon and thin film solar cell, is that it also can work under low irradiance condition such as indirect sunlight for instance under overcast conditions (Mubarak, 2018). DSSCs are shown to be promising low cost solar cells based on organic materials with moderate efficiency. They are inexpensive to prepare and moreover, they can be easily manufactured as they are able to be fabricated on lightweight flexible substrates (Muliani *et al.*, 2013).

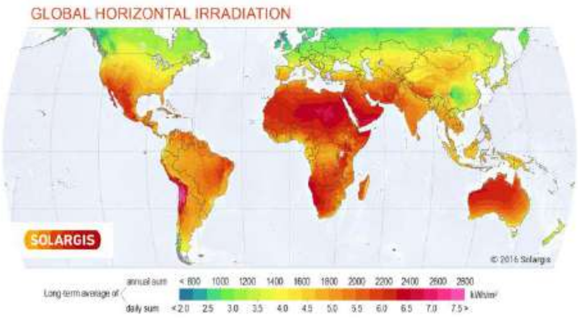

Figure 1. Global insolation map, showing the amount of solar energy received daily and annually on a horizontal surface on the world. (Solargis.com)

A DSSC consists of a TiO_2 semiconductor layer as the photoelectrode that is bonded with dye molecules. The bottom section consists of a counter-electrode that is usually made of platinum material. The general structure of a DSSC is depicted in Figure 2. Typical DSSCs in sandwich configuration consist of two glass substrates that are coated with transparent conducting oxide (TCO). One of the substrates represents the photoelectrode and the other represents the counter-electrode.

In order to make DSSCs, which have lower efficiencies than former generations of solar cells, competitive, further manufacturing cost reductions are needed. Since the TCO-coated glass contribute to at least 60% of DSSC material cost, therefore, a new configuration for DSSCs is developed: the monolithic configuration that uses only one TCO-coated glass substrate instead of two. The separation between the electrodes is done by removing some of the conducting layer and adding a spacer layer that is made of ZrO_2 (Nursam *et al.*, 2017). Recent researches also showed that sandwich DSSC performed better than monolithic DSSC is caused by the charge transfer between the platinum, as counter-electrode material, and the electrolyte was ineffective in monolithic configuration due to platinum material characteristic that is not suitable for monolithic DSSC manufacturing method. In that research carbon proved to have better performance than platinum as counter-electrode in monolithic configuration (Nursam *et al.*, 2017). Our objectives in this research are, first, to analyze the performance of monolithic DSSCs with carbon counter-electrode and to compare it to the performance of sandwich DSSCs with carbon counter-electrode, and, second, to analyze the performance of a DSSC submodule that consists of three cells in monolithic configuration.

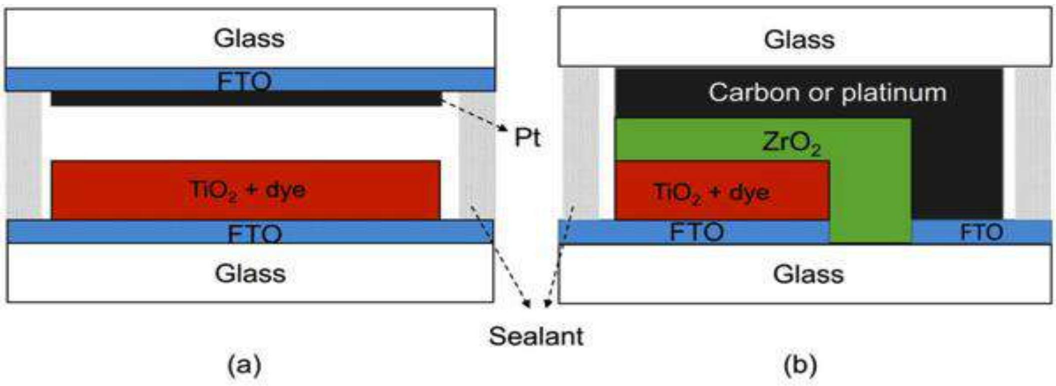

Figure 2. Structure of DSSC with sandwich configuration (left) and monolithic configuration (right).

2. Research Method

This project consists of manufacturing and characterization processes. First of all, the carbon paste for the counter-electrode material was synthesized using the best composition from previous researches that consists of graphite (0,5g) + activated carbon (2g) + TiO2 P 25 (0,25 g) + terpineol (4,25 g) + cellulose (0,3 g) (Arif, 2018). After that, the sandwich DSSCs, monolithic DSSCs and submodules were identically constructed on glass substrates that were coated with fluorine tin oxide (FTO) as the TCO layer, with a TiO_2 layer as photoelectrode and a carbon layer as counter-electrode. The layers were deposited on the substrates using the screen-printing method. In the case of the monolithic configuration, whose electrodes are both on one substrate with an additional ZrO_2 layer as spacer in the middle (Nursam *et al.*, 2017), the cell was encapsulated in silicone gel. Five samples for both monolithic and sandwich DSSCs were made with an active area of 0.25 cm^2 each. Additionally, two samples of monolithic submodules were made. The active area of one cell in the submodule was 3.44 cm^2 so that the total active area of the submodule was 10.32 cm^2. The performance characterization consists of a current-voltage (I-V) characteristics measurement.

3. Results and Discussion

The I-V measurement characterization resulted in the I-V curve and the average performance parameters for the monolithic and sandwich cells that are shown in Figure 3 and Table 1.

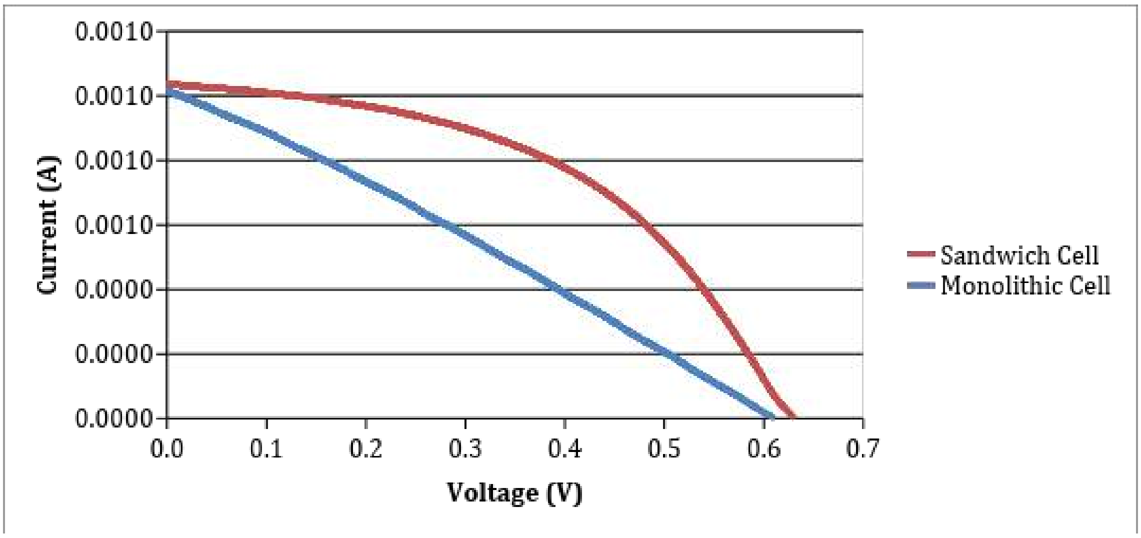

Figure 3. I-V curve for monolithic and sandwich DSSC.

From this measurement the following performance parameters can be derived: short-circuit current, open-circuit voltage, serial resistance, maximum power, fill factor, and light-to-current efficiency (Table 1).

Table 1: I-V characteristic comparison between monolithic and sandwich DSSC (maximum power, efficiency, short-circuit current, open-circuit voltage, fill factor, and serial resistance).

Average	Pmax (mW)	Eff (%)	Isc (mA)	Voc (V)	FF	Rs (Ω)
Sandwich	0.31	2.50	1.03	0.62	0.49	208.40
Monolithic	0.17	1.46	0.99	0.59	0.30	500.74

Quite a big difference can be seen in the fill factor. For the monolithic DSSC it is 0.30, while for the sandwich DSSC it is 0.49. Additionally, the short-circuit current is a bit lower for the monolithic cells, i.e. 0.99 mA compared to 1.03 mA for the sandwich cells. These differences result in an efficiency difference. The maximum power of the monolithic cells is 0.17 mW, while the maximum power of the sandwich cells is 0.31 mW, and the efficiency of the monolithic cells is 1.46%, while it is 2.50% for the sandwich cells. The two cell configurations have a similar open-circuit voltage of around 0.6 V.

The difference of the fill factor between monolithic and sandwich DSSC is caused mainly by the difference on the serial resistance of monolithic DSSC of 500 Ω, which is more than twice as high as the serial resistance of sandwich DSSC of 208 Ω. The high level of serial resistance of monolithic DSSCs is caused by their material structure that consists of solids, especially ZrO_2 with a high resistance, while sandwich DSSCs consist of two electrodes with only liquid electrolytes between the two electrodes.

The I-V curve result on this research on monolithic and sandwich cell with carbon counter-electrode also proved that carbon is a better counter-electrode material for monolithic DSSC compared to previous research on platinum counter-electrode in sandwich and monolithic cell. The FF and internal resistance (Rs) difference between sandwich and monolithic cell with carbon counter-electrode is lower compared to the cells with platinum counter-electrode, because in monolithic DSSC, the porosity factor of the counter-electrode material affected the infiltration of the dye before the dye sensitized the photoelectrode (Hagfeldt *et al.*, 2010; Nursam *et al.*, 2017).

From the five samples of each monolithic and sandwich DSSC, the monolithic DSSCs have a higher consistency in the manufacturing process that requires only encapsulation instead of assembly. Therefore, the number of two submodule samples with three monolithic cells connected in series in each submodule is sufficient for the research. The I-V curve and the performance parameters of the submodules are shown in Figure 4 and Table 2.

Table 2: I-V characteristics comparison between monolithic DSSC and submodule. (maximum power, efficiency, short-circuit current density, open-circuit voltage, fill factor, and serial resistance).

Average	Pmax (mW)	Eff (%)	Jsc (mA/cm^2)	Voc (V)	FF	Rs (Ω)
Submodule	5.90	1.14	3.53	1.68	0.29	121.98
Avg. of submodule cells	1.32	0.77	2.50	0.56	0.27	60.15

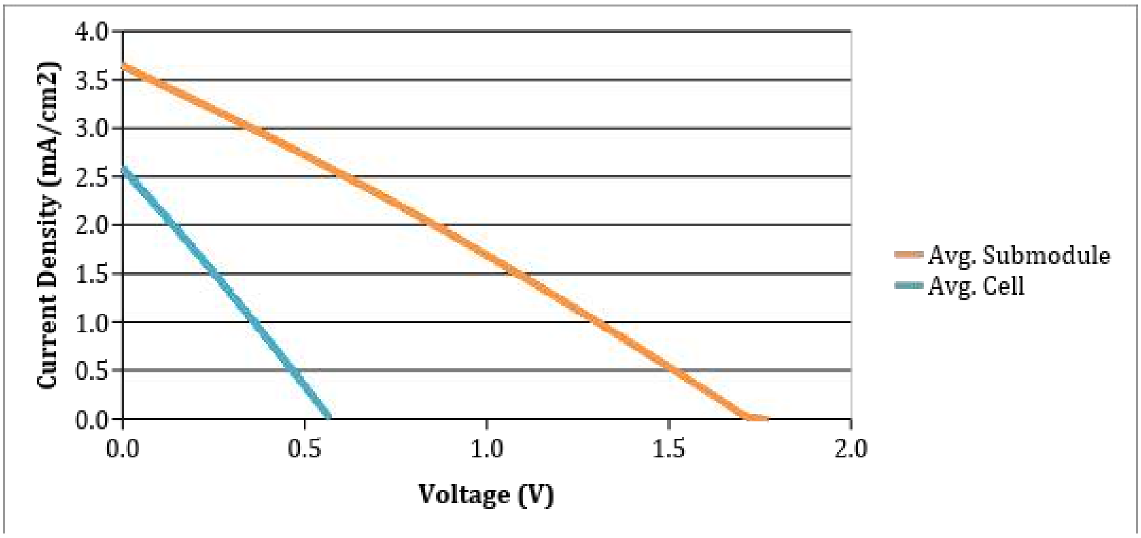

Figure 4. I-V curves of monolithic submodule and the cells.

Both the submodule and the monolithic cells have a similar I-V curve shape and fill factor of around 0.27-0.29. According to the serial connection of the three cells in the submodule, the open-circuit voltage of the submodule is three times the open-circuit voltage of the cells. The measured short-circuit current density of the submodule is higher than the short-circuit current density of the individual cells in the submodule, 3.53 mA/cm^2 versus 2.5 mA/cm^2. The efficiency is higher for the submodule: 1.14% versus 0.77% for the cells. The higher efficiency of the submodule compared to the efficiency of the individual cells in the submodule corresponds to a lower serial resistance. The serial resistance of the submodule, including the contacts was 121 Ω, which is three times lower than the serial resistance of the individual cells (60 Ω). This shows that there is a potential for a more efficient usage of monolithic cells by means of a module design that allows for lower resistances in the interconnection of the cells within the module as well as in the module contacts. This should be pursued in further research, as well as the reduction of the internal resistance of the monolithic cells.

4. Conclusions

Monolithic DSSCs with carbon-based counter-electrode were successfully manufactured. However, they had a high internal serial resistance due to the configuration that consisted of solid materials with a higher resistivity. Due to the higher serial resistance of monolithic DSSCs compared to sandwich DSSCs, monolithic DSSCs had a lower electrical performance compared to sandwich DSSCs. The fill factor was lower as well as the short-circuit current and, hence, the efficiency. The increase in the short-circuit current density and maximum power on the scaled-up monolitihic submodule shows some potential for further improving the performance. More studies about the combination of cells in larger units can be useful in order to evaluate possible performance improvements.

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