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Understanding the Influence of Belt Furnace and Sintering Parameters on Efficiency of Dye-Sensitized Solar Cells (DSSC)

ABSTRACT

Dye-sensitized solar cells are the most cost-effective, third-generation solar technology available today. DSSC technology, invented in 1991 by Michael Gratzel and Brian O'Regan, has recently attracted more interest because of its low material cost, ease of production, and high conversion efficiency compared to other thin-film solar cell technologies. Nonetheless, due to technical constraints, the maximum efficiency is only half the efficiency of crystalline silicon-based solar cells. In an effort to replace the solar technologies we currently use, improving the efficiency of DSSC technology is critical for widespread adoption. The process parameters have a significant impact on determining the efficiency of the solar cell, as well as, the materials being applied. This paper will attempt to summarize the influence of material selection, the sintering process, and belt furnace parameters on the efficiency of dye-sensitized solar cells.

INTRODUCTION

Sintering of the electrode layer (composed of TiO2 and TCO) is an essential step when determining the overall efficiency of the solar cell. The process consists of a two stage sintering procedure where sintering of the layer occurs before and after dye implementation. Important parameters to note are the growth temperature, soaking time, and the heat rate; all of which will directly affect the outcome on the efficiency of the solar cell. Additionally, the materials selected for each segment of the cell will have an integral effect on the final efficiency as well. This paper will explore the ideal sintering process parameters and the material selections, as well as, the impact they both play on the overall efficiency of the solar cell.

DESCRIPTION

A dye-sensitized solar cell is composed primarily of three parts (as shown in figure 1). The first part, the substrate, is the negative terminal. The substrate has a layer of transparent glass on the outside and a coating of transparent conductive oxide (TCO) on the inside. This warrants sunlight to pass through. In the center sector, a layer of dye sensitizers bind to a layer of nano-structured titanium dioxide (TiO2), where the TiO2 is connected to the negative terminal to collect sunlight. All of the layers are then immersed in an electrolyte solution to allow charge transportation. The top part is the positive terminal and it contains a coating of carbon (graphite) or platinum for the purpose of transferring electrons. The outside layer is made of transparent glass and the top and bottom divisions are joined together to prevent the centered portion from leaking.

ELECTRICITY GENERATION SCHEMATICS

Initially, sunlight passes through the transparent conductive oxide (TCO) layer into the dye-sensitized layer exciting the electrons within the molecules. The electrons are then injected into the TiO2 particles (which act as a semiconductor) transporting light induced electrons toward the negative terminal. The negative terminal layer, or the TCO layer, is where all of the electrons are

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collected and then transported to the external circuit, generating electricity. Subsequently, the electrons are reintroduced into the solar cell through the positive terminal into the electrolyte. From here, the electrolyte transports the electrons back into the dye molecules and the process is repeated.

MATERIALS SELECTION

The transparent coating for the negative terminal is made of a thin layer of fluorine-doped tin oxide. It is a substrate that enables sunlight to pass through it, conducting electricity.

For the semiconductor, either zinc oxide (ZnO) or titanium dioxide (TiO2) can be applied. TiO2 is the preferred choice and it is used most often because the surface is highly resistant to continuous electron transfer. Titanium dioxide, however, is not sensitive to visible light and it will only absorb a small amount of solar photons. Therefore, dye sensitizers have to be joined together with the titanium dioxide layer in order to harvest large portions of the sun's light. Zinc oxide has higher electron mobility than titanium dioxide, however, it has a limited selection of organic dyes. This makes it a less suitable option until more exceptional alternative sensitizers are identified.

Dye-sensitizers can contain several classifications of materials. One option, the natural dye, can come from a variety of resources such as blue berries, blackberries, and raspberries. They are the easiest to come by and are excellent for student training courses and/or for testing purposes. A second option, the synthetic dye, provides better performance because of its optimized light collection property.

The material used for the positive terminal layer, or the cathode layer, can be platinum or carbon (graphite). Platinum is more efficient, however, the carbon alternative is the easiest and least expensive to use (great for school work or testing purposes).

ADVANTAGES

The advantages of DSSC compared to alternative options for solar electrical generation, is that DSSC has a high price/ performance ratio. This means that it is less expensive to assemble, as well as, light and mechanically robust due to its material properties. With its ultra thin profile, the cells can be constructed into several shapes in order to meet the specific requirements for its design. Furthermore, due to its robustness, DSSCs maintain their efficiency at high temperatures. The efficiency of the DSSC is between 10% and 11%, which is higher than other thin-film solar panels having an efficiency of only about 5% to 13% on average. DSSC technology also operates in low-light conditions (for example: cloudy weather where there is no direct sunlight), which is another reason why the DSSC is highly attractive among current choices for solar electrical generation.

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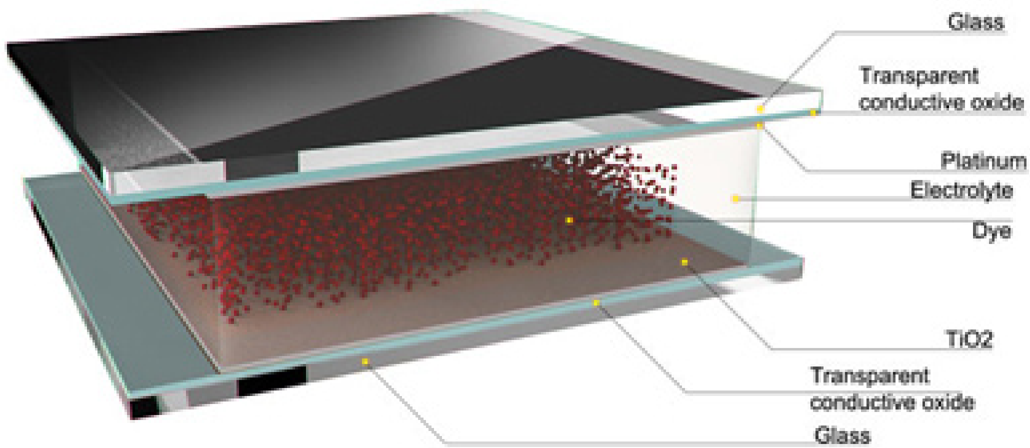
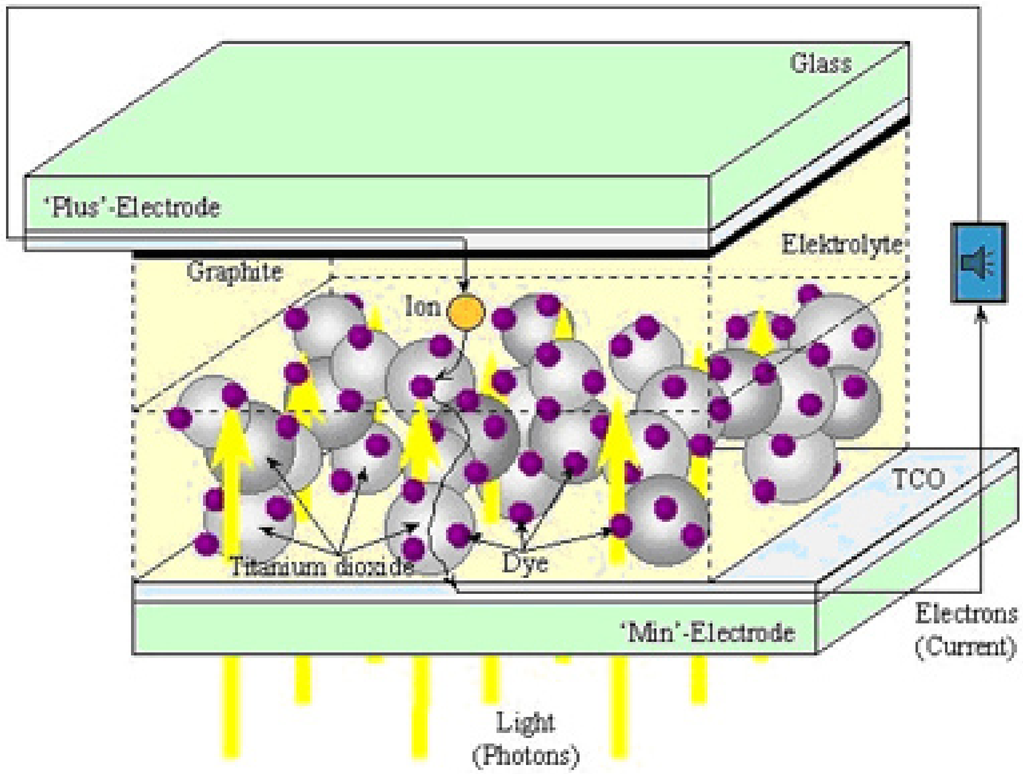
DSSC Schematic



Source: SolarPrint



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PROCESS OF SINTERING IN A BELT FURNACE

To start, the titanium dioxide layer is compounded by sintering TiO_2 nanoparticles at a temperature range of 300 °C to 500°C. The sintering process takes place on the transparent conductive oxide (TCO) glass plate, which is put into a uniformly heated furnace for about twenty minutes. This process omits the ambient moisture within the Titania layer, which is needed to ensure the electrical contact between the titanium dioxide nanoparticles and a worthy adhesion to the TCO (transparent conductive oxide) glass plate. Sintering of the layer can be executed at 150 °C, however, its performance power will be lower than those sintered at 450 °C (mentioned in P.M. Sommeling research paper; ECN Solar Energy). The layer is then soaked in the dye solution so that the dyes can be absorbed into the TiO_2 surfaces. Finally, the layer is inserted into a drying furnace where the titania is baked at 100 °C, and then sanctioned for cooling.

INFLUENCE OF SINTERING TEMPERATURE ON PERFORMANCE OF DSSCS

Extensive research has been accumulated on the effects of various temperatures and the efficiency of the DSSC. The current ideal firing temperature is preferred around 450-500 °C, as shown below. High sintering temperatures at 450 °C result in a more desirable contact between the nanoparticles and a stronger adhesion to the substrate than those sintered at lower temperatures. It is important to keep in mind, however, that the DSSC will become unstable at very high temperatures because they have an upper limit of 600 °C to 650 °C.

SINTERED FOR 60 MIN

Temperature °C	Time (min)	ZnO Efficiency (%)	TiO_2 efficiency (%)
100	60	0.55	
200	60	0.64	0.8
300	60	0.78	
400	60	1.06	1.29
500	60	0	

Below is alternative results discovered through experimental research

Temperature °C	Time (min)	Average particle size (nm)	TiO_2 efficiency (%)
100	60	9.8	1.4
150	60	10.7	1.49
200	60	15.3	2.59
250	60	18.9	4.25
300	60	22.5	5.19

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The temperature profile comparisons clearly indicate that higher sintering temperatures result in larger TiO_2 nanoparticles. Which, in turn, result in an overall improvement on the efficiency of the solar cell. The reason being that the larger particles allow for prominent dye absorption, producing higher electron generation.

THE SINTERING TEMPERATURE LIMIT

Temperature °C	Time (min)	Efficiency (%)
500	1	0.1
500	15	2.6
500	30	2.9
600	30	2.6
800	30	0.2

The temperature upper limit is around 600 °C. As you can see, the efficiency drops suddenly due to the instability of the TiO_2 nanoparticles.

In conclusion, a sintering temperature between 400 °C and 500 °C will result in a highly efficient DSSC.

FURNACE FOR DSSC APPLICATION

The HSK series furnace is an energy efficient precision thermal processing system specifically designed, and most often used, for DSSC applications. It has six channel temperature profiling units for independent temperature profiling with an LCD data display and check, analysis software, sampling unit, 3 T.C., and an RS232 CPU interface. The HSK Series is designed to support continuous on/off heating and cooling cycles resulting from alternating production periods and inactive operation. The heating length of the HSK Series is 3220mm (127") and includes seven independently controlled heat zones. Process materials are transported through the furnace on a belt that is 350mm (14") in length with 50mm (2") of product clearance. The speed of the belt ranges from 40-200mm (2"-8") per minute and is administered using a digitally displayed variable frequency motor controller. The belt speed is also programmable in IPM with readout right on the PC. The belt material on the HSK Series furnace is Nichrome V mesh (Balanced Spiral) and operates from 480V, 3 phase, 5 wire, 60Hz with a maximum load connection of 42kVA.

The performance of the HSK Series furnace is unparalleled as it can protect itself from over heating, over loading, and low gas pressure. It has an ultra-clean low-mass refractory heating chamber that can increase heat from ambient temperature to 1,050°C in approximately 40 minutes. The temperature of the furnace is controlled by a microprocessor that typically operates from 200-900°C. Each zone is managed using a high performance, single ASIC full auto-tuning PID and a single loop intelligent temperature controller. The HSK Series atmosphere distribution and management system can terminate thermal shock and process contamination, as well as, extract burn-off effluents across the entire width of the chamber for yield improvement. The HSK Series is assembled with entrance/exit curtains and an air powered Venturi exhauster (200mm /8" in diameter) to keep the firing chamber clean while, at the same time, improving temperature stability for drying and firing. The exhaust flow can also be easily adjusted using the flow meter. The HSK Series is readied with a redundant overheating safety protection system that incorporates a type "K" thermocouple (located in the center of each heated zone) and a multi-loop alarm. It ensures consistent 'firing' results because of its exceptionally reliable temperature uniformity control. The HSK Series furnace has a removable condensate collection trap and provides emergency off buttons located at each end of the furnace (connected to a 24v emergency off circuit). To see a complete list of the HSK Series specifications please see the chart below.

Specification	HSK2505-0611	HSK3505-0711	HSK6305-0711
Rate Temperature	1050 °C	1050 °C	1050 °C
Belt Width	250mm/10"	350mm/14"	635mm/25"
Tunnel Height	50mm/2"	50mm/2"	50mm/2"
Heating Length	2160mm/85"	3220mm/127"	3220mm/127"
Cooling Length	1200mm/47"	1200mm/47"	1200mm/47"
Control Zones	6	7	7
Conveyor Speed	40-200mm(2"-8")/min	40-200mm(2"-8")/min	40-200mm(2"-8")/min
Overall System Width	1040mm/41"	1100mm/43"	1400mm/55"
Overall System Length	5800mm/228"	7000mm/276"	7000mm/276"
Overall System Height	1350mm/53"	1350mm/53"	1350mm/53"
Typical Temp. Uniformity	+/- 2 °C	+/-2 °C	+/-3 °C
Net Weight	1000kg	1600kg	2000kg
Power	240V, 3 phase, 60HZ, 5 wire, 36KVA	240V, 3 phase, 60HZ, 5 wire, 42KVA	240V, 3 phase, 60HZ, 5 wire, 56KVA
Spare Part	1 set heating board, 1 solid relay, 2 relays, 2 switches	1 set heating board, 1 solid relay, 2 relays, 2 switches	1 set heating board, 1 solid relay, 2 relays, 2 switches

BELT FURNACE PARAMETERS

Cleanliness, atmosphere, temperature controller, sensors

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For more information on belt furnaces and silicon solar cell manufacturing please go to http://www.beltfurnaces.com for details.

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