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Development of Dye-Sensitized Solar Cell for High Conversion Efficiency

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1. Introduction

The Solar cell energy is presently promising because of oil inflation, fuel exhaustion, global warming, and space development. Many advanced countries rapidly develop the solar cell energy under a nation enterprise. Particularly, dye-sensitized solar cell (DSC), the 3rd generation solar cell, has low-cost of manufactures about 1/3~1/5 times compared with the silicon solar cell, which encourages the research globally.
Dye-sensitized Solar Cell (DSC) is evaluated to be low-cost technology as the manufacturing DSC is more inexpensive 5 times than producing Silicon Solar Cell. Currently, the best conversion efficiency is 11%, the tile-shaped modules are being produced in STI, Austria. Moreover the efficiency to increase over 15% and the process of fabricating DSC for commercialization are attempted to be highly researched.
Recently, production of nano-particles becomes available due to development of nano-technologies. Since they have broad contact area comparing to the existing compound materials being generally used and increased mechanical, thermal and electrical characteristics, etc., they are attracting public attention as a new material to implement various functions. Especially, nano-tube has more excellent mechanical and electrical characteristics than normal particle type materials. And it is known that the smaller its diameter, i.e. aspect ratio, is, the better its characteristics are. Accordingly a lot of researches related to nano-compound materials have been being progressed nationally and internationally (Gojny et al., 2003; Jijima, 1991; Chang et al., 2001).
It is new methods to improve light conversion efficiency using several approaches such as nanocrystalline CNT/TiO_2 hybrid material, reflect mirror with micro pyramid structure, and concentrating light with Fresnel lens.
Figure.1 shows the operational principle and structure of dye sensitized cell. If visible rays are absorbed by n-type nano particles TiO_2 that dye molecules are chemically absorbed on the surface, the dye molecules generate electron-hole pairs, and the electron were injected into the conduction band of semiconductor's oxides. These electrons that are injected into the semiconductor's oxide electrode generate current through each nano particles' interfaces. The holes that are made from dye molecules are deoxidized by receiving electrons, thus causing the dye-sensitized cells begin to work (Zhang et al., 2010).

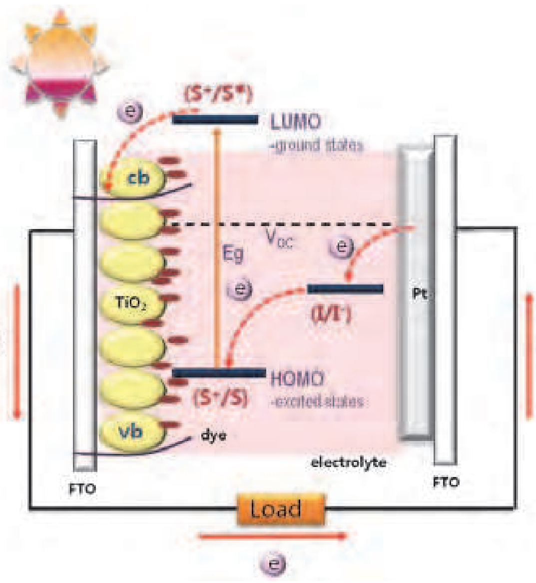

Fig. 1. A schematic representation of the construction of a DSSC

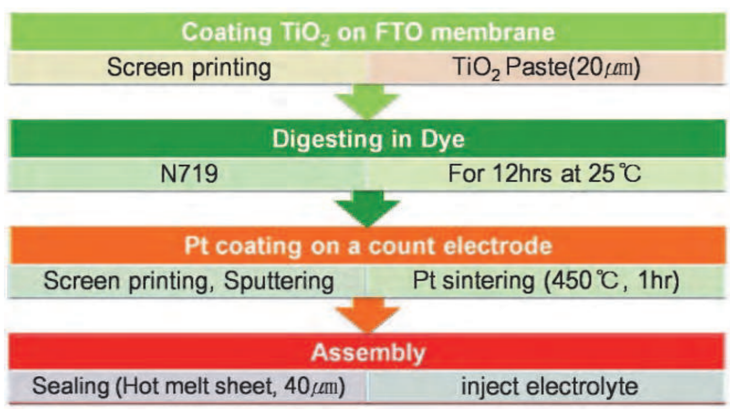

Fig. 2. Process of manufacturing DSSC

We applied screen printing method on FTO membrane to TiO_2 paste in 20μm. Coated working electrode membrane was sintered at 450°C and digested them into dye (N719) for about 12 hours.

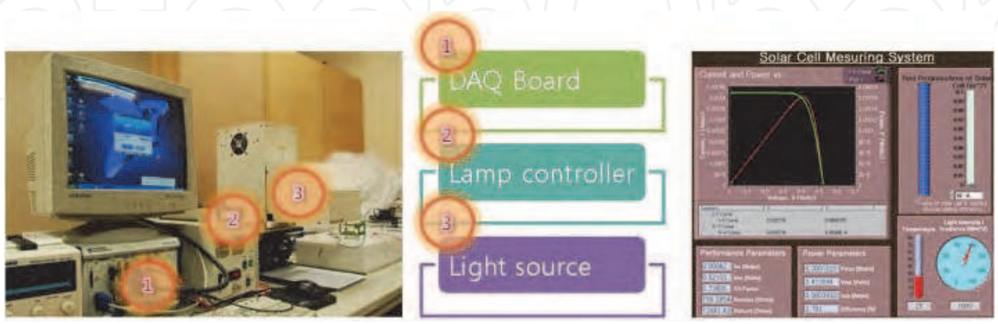

Fig. 3. Measurement system and program

In order to understand efficiency increase of solar cells due to coating method, we compared individual efficiencies using solar cell simulator. Measuring efficiency of solar cells had been progressed under AM (air mass) 1.5 conditions (1sun, 100mW/cm²).

2. A study of photocatalyst of the TiO_2 thin film with acid dispersed CNT

As one of major variables of dye-sensitized solar cell, the dye absorbed light energy transits from ground state to excited state and gets electron injection. Electrons are injected in a very fast speed of femtosecond or picoseconds unit and oxidized dye is renewed within several nanoseconds. On the other hand, since rejoining speed that the electron becomes dissolved into electrolyte via surface state is slow such as micro seconds or milliseconds and most of photons are injected semiconductor conduction band, those electrons that are not injected meet holes again to be restored and decrease efficiency of solar cell. If we utilize CNT that is advantageous for electrical and thermal conduction as a compound material, we can increase electron injection speed than rejoining speed and increase efficiency of dye-sensitized solar cells through movement of more electrons.

Since multi walled carbon nanotube (MWCNT) is a material to well transfer electricity and heat, it can function as a basic electrode. Nanotubes function as electrodes to penetrate into broad TiO_2 surface mutually and assist extracting charge carriers efficiently from dye layer. Since these electrodes are very clear under longer wavelength, they are advantageous for solar light spectrums.

This study utilizes CNT that is advantageous for electrical and thermal conduction as a compound material so that surface resistance between clear electrodes and dye layer decreases, electron injection speed can be increased more than the rejoining speed of electrons and efficiency of dye-sensitized solar cell can be also increased through movement of more electrons. In order to perform the task, this study will composite nano-crystal TiO_2 with sol-gel technique (Tracey et al., 1998), establish optimal thin film formation conditions through identification of correlation between permeability and conductivity by manufacturing distributed CNT through acid treatment and compound thin film, and perform characteristics assessment by applying it to solar cells upon surface resistance between dye layer and FTO.

Dye-sensitized solar cell is a device to apply photosynthesis principle of the plant by combining pigments to absorb light energy within chloroplast with polymer and applying them to the solar cell. Dye-sensitized solar cell basically consists of dye polymer to absorb solar light, semiconductor compound having broad band gap serving as n-type semiconductor, electrolyte serving as p-type semiconductor, relative electrode for catalysis, and clear electrode to permeate solar light. Dye-sensitized solar cell is composed of semiconductor nanoparticles where dye absorbs solar energy and separation/transfer of generated electrons are diffused upon electron concentration difference. Processes to generate and transfer electrons play an essential role to determine performance of the cells. Firstly entering time of excited electrons from the dye into TiO_2 should be shorter than that of joining with holes and being exterminated. Normally entering time of electron is very fast in femtoseconds through picoseconds and oxidated dye is renewed within several nanoseconds (Tachibana et al., 1996).

2.1 Composition of TiO_2

Manufacturing methods of TiO_2 for photocatalyst generally includes hydro thermal method (Chen et al., 1995), sedimentation method (Ellis et al., 1989; Lee et al., 2000), sol-gel technique (Ding et al., 1995; Johnson, 1985; Hwang & Kim, 1995), CVD method (Lee et al., 1999), etc. Hydro thermal method that may get mainly powder materials has complex equipment and difficult for continuous work, while sedimentation method allows easy production but it has disadvantages cohesion between particles, powder with possibility of uneven composition, and difficulties for fineness as bulk materials from sintering and harmonization of crystalline. Comparing to them, sol-gel technique has advantages to allow easy acquisition of TiO_2 powder for photocatalyst with even composition relatively simply and low temperature composition available.

2.2 CNT dispersion

Carbon nanotube exists as a form of bundle or cohesion body due to strong van der Waals forces between tubes as like interaction between graphite plates. This cohesion phenomenon obstructs formation of 3-dimensional network structure in manufacturing compound to increase electrical or mechanical properties. It is an important technology to disperse carbon nanotube and release individual strand, as it increases functional efficiency. Dispersion methods of carbon nanotube can be classified into mainly mechanical dispersion, dispersion using strong acid, dispersion with solution, etc. Firstly, dispersion using strong acids is to agitate with composition of nitric acid and hydrochloric acetone at 130°C for 6h or using composition of sulfuric acid and hydrochloric acid. Dispersing with solution is to melt carbon nanotubes through surface active agents such as SDS (sodium dodecyl sulfate), Triton X-100, LDS, etc. The most various mechanical dispersion methods include supersonic treatment by mixing acetone and methanole, or using ball milling method to minimize length and diameter distribution of carbon nanotubes. Others include dispersions with grinding process using mortars, abrasion process, high shear strength using liquid, etc.

2.3 Experiment method and conditions

2.3.1 Production and coating of CNT/TiO_2

TTIP that is used for this study generates photocatalyst TiO_2 under low temperature heating conditions but it has a disadvantage fast hydrolysis with air or small moisture due to very string reactivity. So we had made even chelate compound by adding AcAc into the ethanol solution and severely agitating it for 30 minutes at room temperature using agitator in order

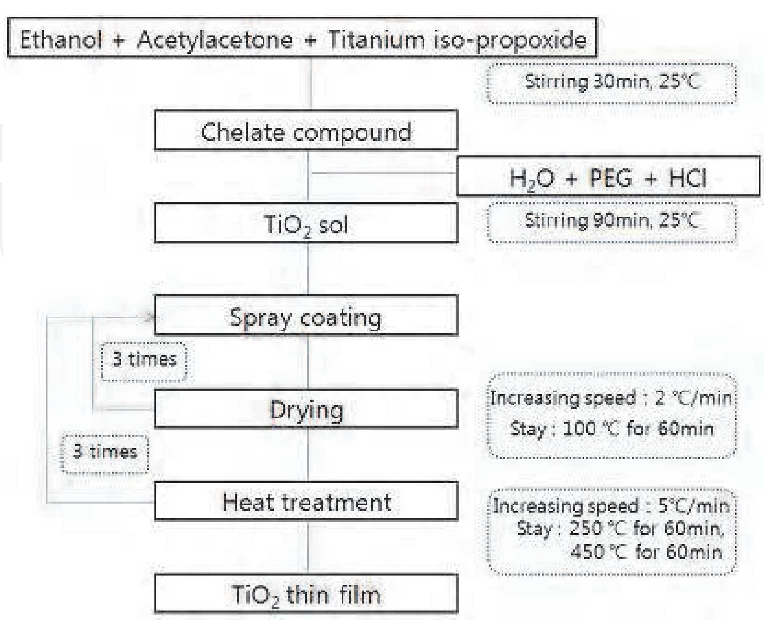

Fig. 4. Process of fabricating TiO_2 Thin Film

to control hydrolysis speed of TTIP. And we have prepared water solution by melting HCl 0.15 mole catalyst for stability of sol and PEG 0.5 mole adhesion to increase osculation with plate to be coated into 50mole distilled water and drop it into the chelate compound. At the moment, it is possible to manufacture yellow clear sol by severely agitating and reacting chelate compound at room temperature for 90min.
For dispersion of CNT, we mixed 60% nitric acid and distilled water in 1:3 volume ratio and severely agitated it at 130°C for 6h. After acid treatment, we mixed a lot of distilled water, apply ultra sonication and continued to neutralize it using PTFE thin film filter with 1um in diameter until it has been neutralized.
In order to understand permeability and electrical characteristics of composited TiO_2 sol and dispersed CNT by concentrations, we have mage mixture solution by establishing variables with Volume% concentrations 0.5, 2.5, 5 and 10.
This study with TiO_2 thin film manufacturing method using sol-gel technique has an advantage to allow applying various processes such as dip-coating method, spinning method, Spray, etc. As spray coating out of them has advantages such as uniform thickness, various compositions to manufacture films by mixing solutions, no big influence from viscosity of solution comparing to spinning method, and available coating without influences from patterned plate, plate surface energy or roughness. It is considered that it is the most appropriate for commercialization as it allows easy manufacture and application of broad area plate.

2.3.2 Manufacture of Dye-sensitized solar cell

We applied composited CNT/TiO_2 to screen printing on FTO plate to coat about 3μm in thickness and coated TiO_2 paste from Dyesol in 15μm. Then we could increase the whole efficiency of cells by decreasing surface resistance between TiO_2 layer absorbed with dye and FTO plate and assisting movement of electrons. Fig. 3 shows coated plated by CNT concentrations, from which we can see that these plates with high content of CNT have thicker colours. We sintered them at 450°C and digested them into dye (N719) for about 24 hours. We coated platinum onto FTO plate with relative electrode and sintered it at 450°C. We sealed prepared 2 plates with Hot melt sheet having about 60μm in thickness and completed them by injecting electrolyte.

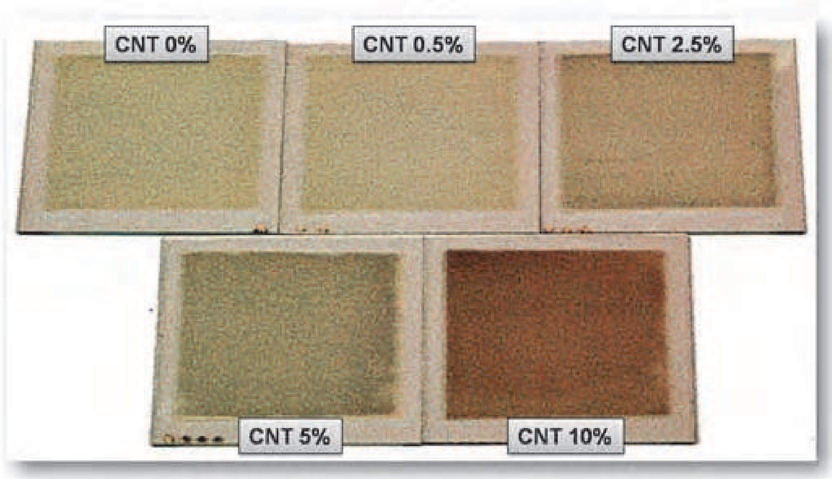

Fig. 5. Feature of CNT/TiO_2 thin film by screen-printing

2.4 Conclusion and considerations

2.4.1 Change of permeability upon CNT concentration

In order to check permeability and electrical characteristics of CNT by concentrations, We coated glass plate with about 5μm in thickness using spray technique, and produced TiO_2 thin film by increasing temperature and sintering it at 450°C for 1 hour. Fig. 6(a) shows composited CNT/TiO_2 thin film surface with very small and even particle. In case of (b), it shows thin film surface of TiO_2 paste from Dyesol with uneven large particles but very excellent porosity. From the results of measurements for permeability of each thin film, as CNT content increases, permeability drops straight and reaches only 10% when concentration becomes 5, 10%.

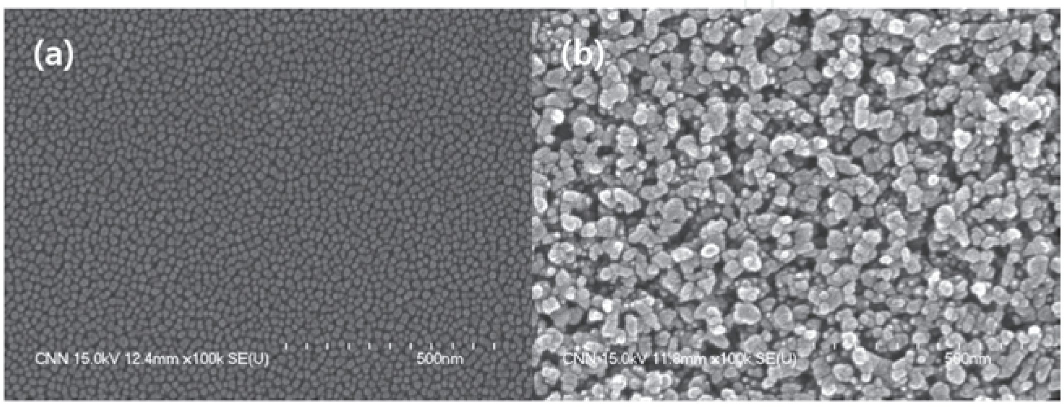

Fig. 6. SEM images of CNT/TiO_2 (a) and TiO_2 paste(b)

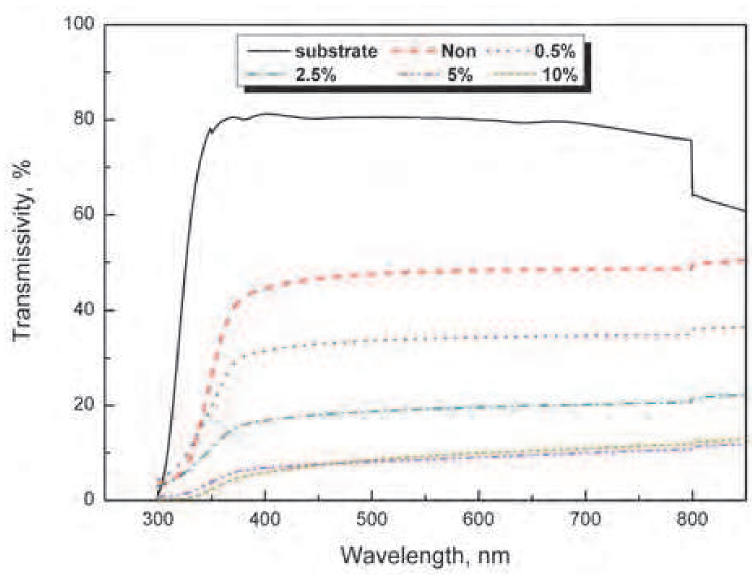

Fig. 7.Transmissivity of TiO_2 layers

2.4.2 Change of surface resistance upon CNT concentration

Fig. 8 shows measurement results of surface resistances upon CNT concentrations. It shows a graph acquired upon each condition by increasing voltage from -1V to 1V by 50mV interval. As CNT concentration with excellent electrical characteristics increases and surface resistance becomes low, it is considered that it would be advantageous for transfer of electrons separated from the dye.

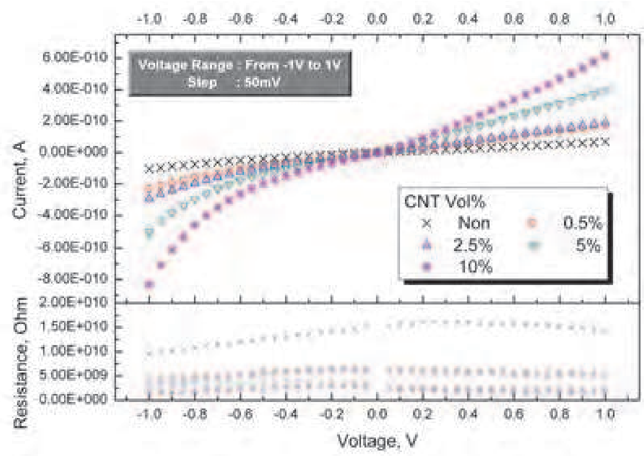

Fig. 8. I-V curve and resistance of TiO_2 layers

2.4.3 Efficiency change of Dye-sensitized solar cell upon CNT concentration

Fig. 9 shows I-V and P-V curve of CNT 0.5% indicating the highest energy efficiency out of CNT concentrations. Efficiency can be calculated from output power by estimating voltage (V_{mp}) and current (I_{mp}) to achieve the maximum output from I-V curve when strength of solar light becomes input power.

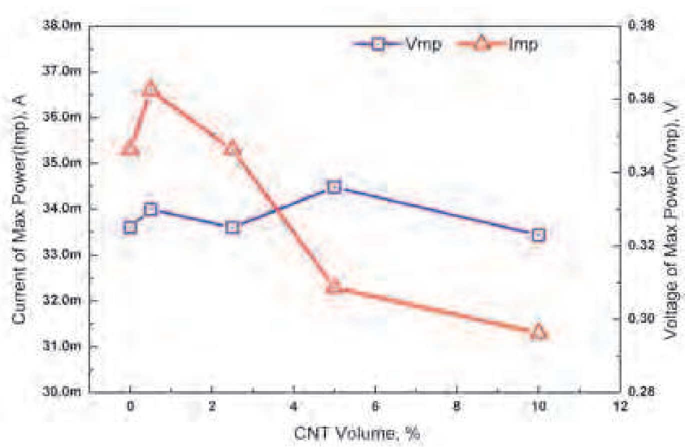

Fig. 9. I-V and P-V curve of DSC with CNT 0.5%

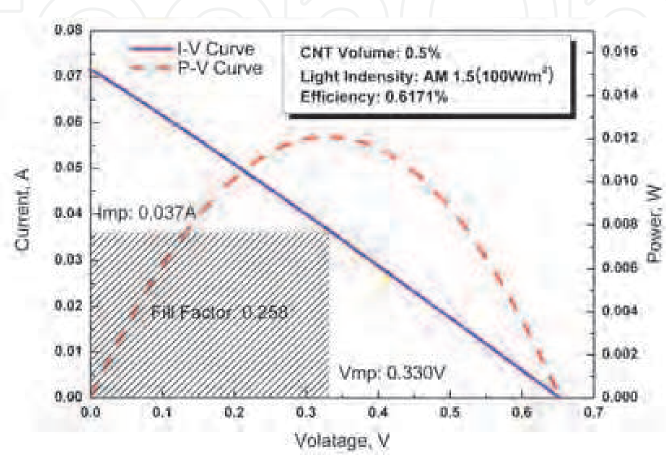

Fig. 10. I_{mp} and V_{mp} of DSC of each CNT volume

In order to confirm if movement of electrons increases according to content of CNT within CNT/TiO_2 compound material, we compared V_{mp} and Imp values upon each condition on Fig. 10. V_{mp} values refer to voltage values when solar cell performs the maximum power, and CNT contents show relatively even values throughout the whole areas. In case of Imp, we can see that it shows high value on very low CNT content such as 0.5%. It means that a lot of electrons are transferred comparing to no CNT, in spite of low generation of electrons due to low permeability. Under high CNT content, such as 5, 10%, we can see that generated electrons are small as surface resistance is low but permeability is low.

2.5 Conclusions

This study has confirmed efficiency of solar cells upon impact of permeability and surface resistance by manufacturing CNT/TiO_2 compound material to increase transfer of electrons separated from dye layer using sol-gel technique as a variable having effect on efficiency of dye-sensitized solar cell and applying in to the solar cells.

- It was possible to develop CNT/TiO_2 compound material to remarkably reduce surface resistance of solar cells and increase efficiency of them and acquire the highest efficiency at 0.5% Vol concentration of CNT.
- It is concluded that as CNT concentration increases, surface resistance becomes low with excellent electrical characteristics, but the solar cells reacting against solar light receive large influence from permeability.
- High permeability increases voltage of solar cells and CNT/TiO_2 compound material with low surface resistance effectively transfers electrons generated from the dye, so they contribute to increase of the current.

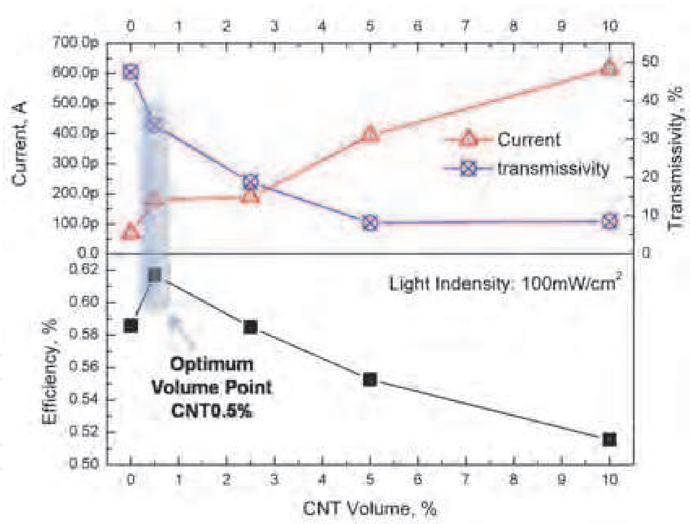

Fig. 11. Determine of optimum CNT volume of DSC

3. The recovery of light with a reflector of microstructures

We have studied a reflector recovering the loss light for improvement conversion efficiency of DSC. One of methods to increase efficiency of dye-sensitized solar cell is to expand surface area of semiconductor oxide such as TiO_2. Since dye polymer has high efficiency when it is absorbed on the semiconductor as a single molecule layer, solar light absorption becomes larger as the surface area of the semiconductor on which dye polymer is absorbed

is wide. Consequently efficiency of the cell is improved as TiO_2 particles are small and porousness is high. This study has researched that the dye produces electrons as much as possible using a method to lengthen scattering distance by reflecting entered solar light rather than expanding surface area of the oxide.
The reflector angle was determined by optical analysis program. Micro pyramid patterns with the 112.6° were processed using the ultra precision shaping machine in order to maximize the conversion efficiency due to increasing light distance. In addition, a comparative study carried out about the conversion efficiency. We made the DSC that is attached reflector with mirror angle 112.6° below. We measured conversion efficiency of solar cell by solar simulator that can irradiate 100mW/cm² (1Sum, AM 1.5).

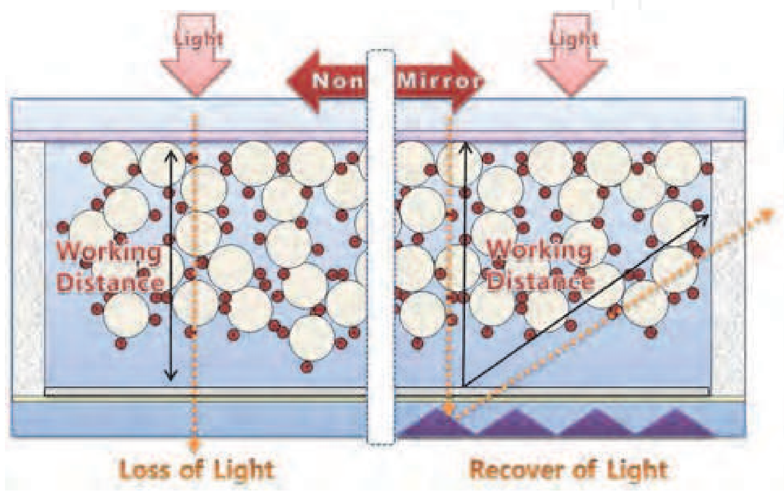

Fig. 12. Scheme of DSC with reflector

As a result of this experiment, the DSC with micro pyramid mirror improves efficiency about 2% against the DSC with black plate. Reflected light can cross more dye of TiO_2 Layer. Therefore, Voltage of maximum power (V_{mp}) increases other reflector with different mirror angle.
We propose a new method to improve light conversion efficiency using a reflector to collect light being lost from permeation through the dye-sensitized solar cell. The goals of this study are to

- Fabrication of reflector with microstructure
- Improve working distance of scattering light
- Control mirror angle by optimum design
- Improve photoelectric efficiency with micro pyramid arrayed mirror

3.1 Light simulation

We designed a micro reflector to lengthen scattering distance of reflected solar light on the dye layer of dye-sensitized solar cell using light analysis program.
In order to maximize light scattering distance of dye layer, we allowed value of Light Angle (θ_l) to be the maximum so that reflected light can be spread out widely on the dye layer. Light Angle and Mirror Angle (θ_m) are indicated on Figure 13. We measured Light Angle according to aspect ratio of height and width of micropattern of the reflector, and determined Mirror Angle when this value became the maximum. Result values of analysis according to Aspect Ratio values are indicated on Table 1 and Figure 14.

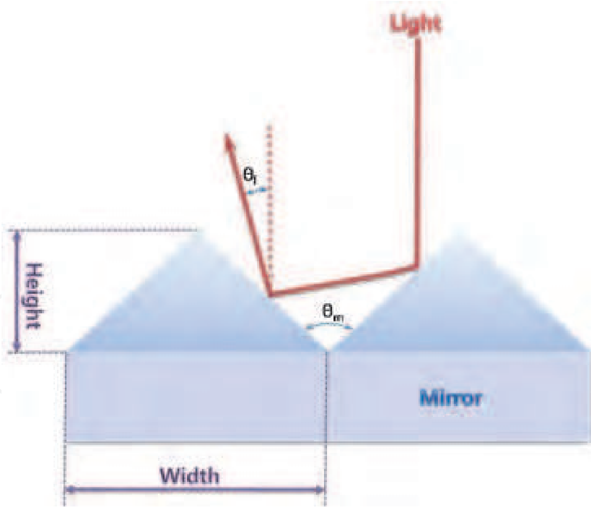

Fig. 13. Scheme of light path and mirror angle

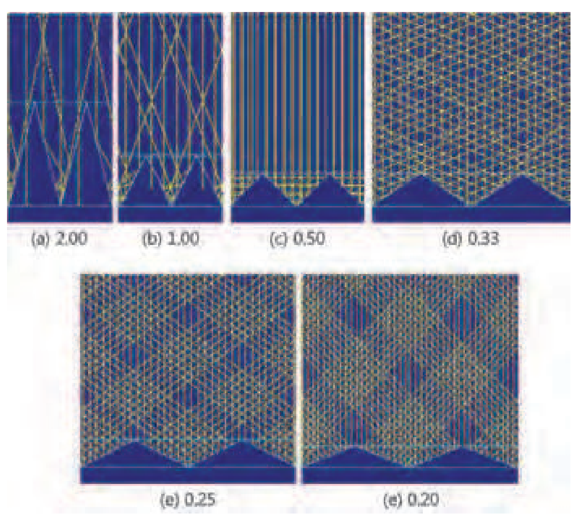

Fig. 14. Simulation results pursuant to aspect ratio

Aspect Ratio	Height [μm]	Width [μm]	Mirror Angle [degree]	Light Angle [degree]	Working distance [μm]
2	50	25	28.8	11.6	40.8
1	50	50	53.2	21.2	42.9
0.5	50	100	90.0	0.0	40
0.33	50	150	112.6	67.5	104.5
0.25	50	200	126.9	53.6	67.4
0.2	50	250	136.4	43.8	55.4

Table 1. Results of light simulation

The results of light analysis said that when Aspect Ratio was 0.33 and Mirror Angle was 112.6°, Light Angle had max value of 67.5°. At the moment, considering that thickness of dye layer of dye-sensitized solar is 40μl, solar light can meet the largest amount of dye with about 104.5μm of scattering distance.

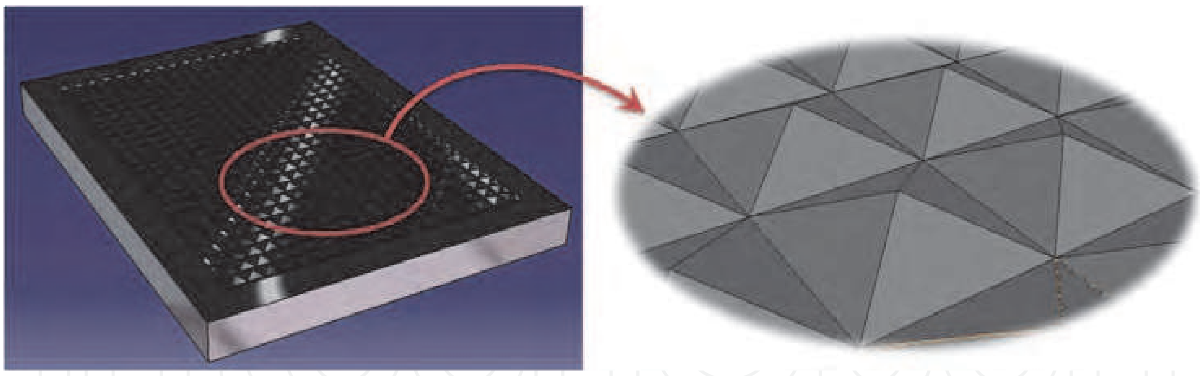

Fig. 15. Modelling of microstructure arrayed mirror

3.2 Fabrication of a reflector

In case of creating micropatterns on the material through micro cutting using single crystal diamond tool, pattern dimensions such as height, width and length of the micropattern depend on shape, cutting depth and feeding amount of the machining tool. In case of shaping machining of material using single crystal diamond having a certain tool angle, its sectional shape has 3-dimensional structure of pyramid shape. In order to machine pyramid shape, process consisted of machining one axis with diamond shaping machining and machining other axis by rotating table by 90° (Kim, 2005).

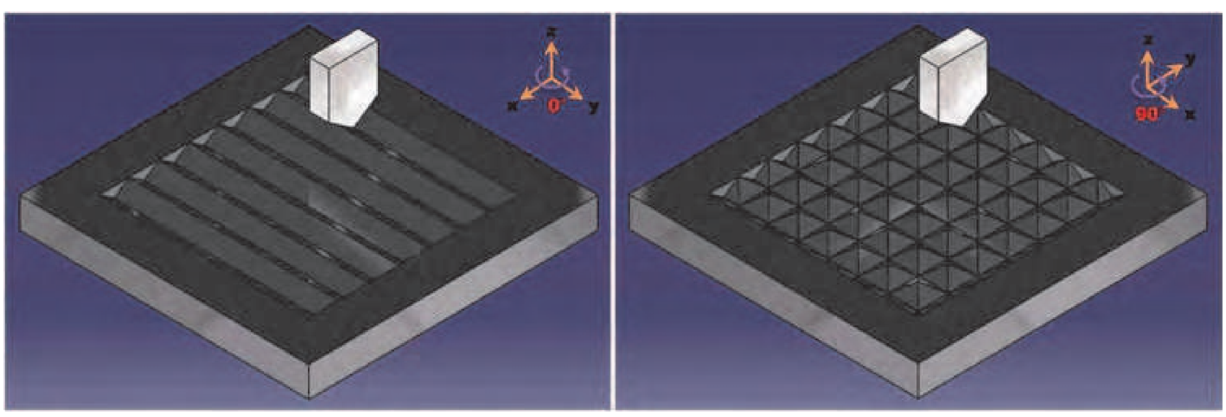

Fig. 16. Tool path of Pyramid shape

For machining sample, Oxygen Free Copper (OFHC copper) to be mostly used for general reflector mirror, etc. has been used. From the results of light analysis, a single crystal diamond bite with s112.6° of tool angle to maximize Light Angle has been used. Cutting length was total 50μm with 5μm steps, and feeding interval was 100μm. Height of mound of machined material was about 33.35μm. After machining, material was washed with supersonic wave to remove micro burr or chip, etc. generated from machining, treated with acid for about 15 seconds with fluoric acid and coated with gold through electrolytic plating. Micropattern machining experiment had been performed using commercial super precision machine. Shape of micro machined sample had been measured using SEM. Figure 18 shows pyramid shaped reflector machined by shaping machine and has 100μm width and 33.35μm height with tetrahedron shape. There was burr generated at the bottom of micro machined work that would be created during 90°rotation machining. It is considered to study machining conditions of cutting amount and feeding speed.

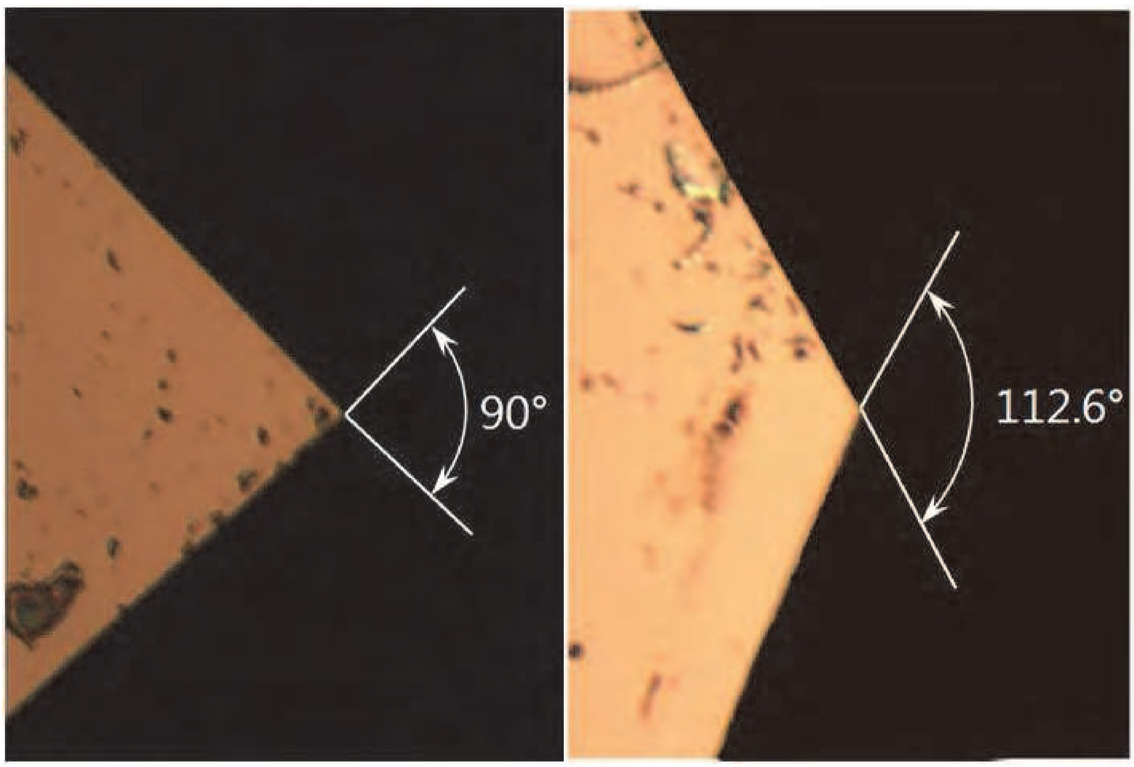

Fig. 17. Images of single diamond tool

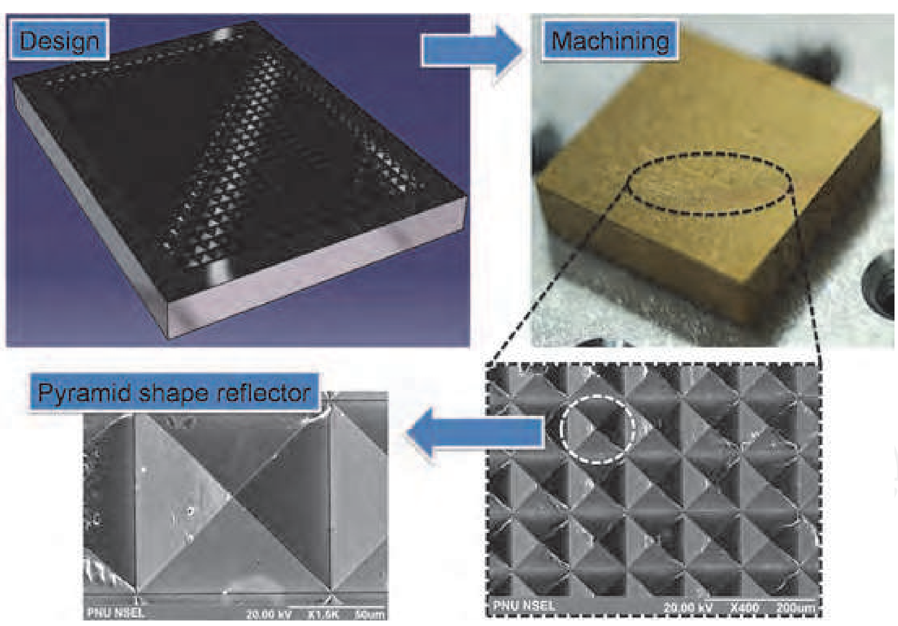

Fig. 18. Machined pattern for reflector

3.3 Results

We made DSC by handmade which of size is 11mm x 4mm. It is smaller area than my precedent study that obtains about 0.5% of efficiency. And size of mirror also becomes smaller before. Figure 19 shows I-V and P-V line diagram in order to measure efficiency of the cell by attaching a black plate at the bottom of dye-sensitized solar cell, pass-through of light in figure 20, and pyramid shaped reflector in figure 21.

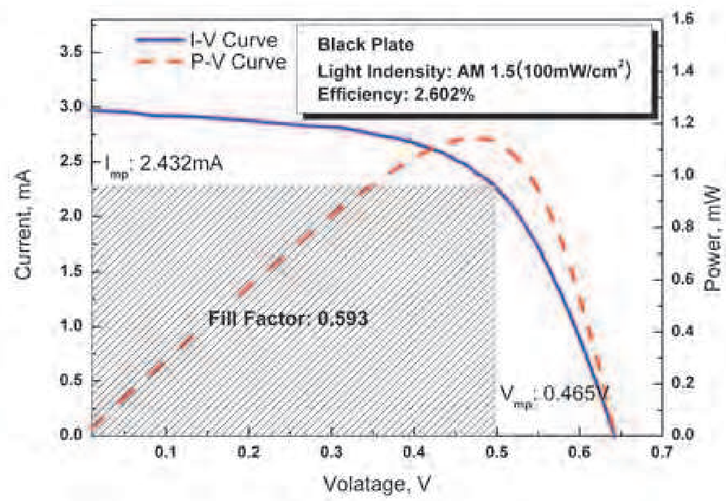

Fig. 19. I-V and P-V curve based on black plate

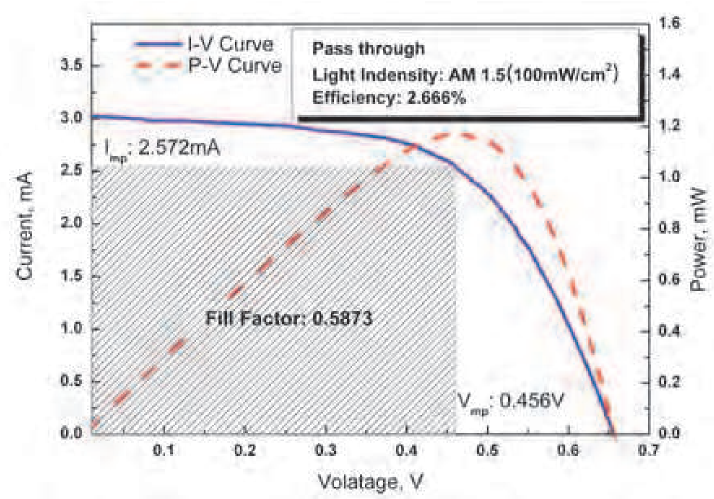

Fig. 20. I-V and P-V curve without a reflector

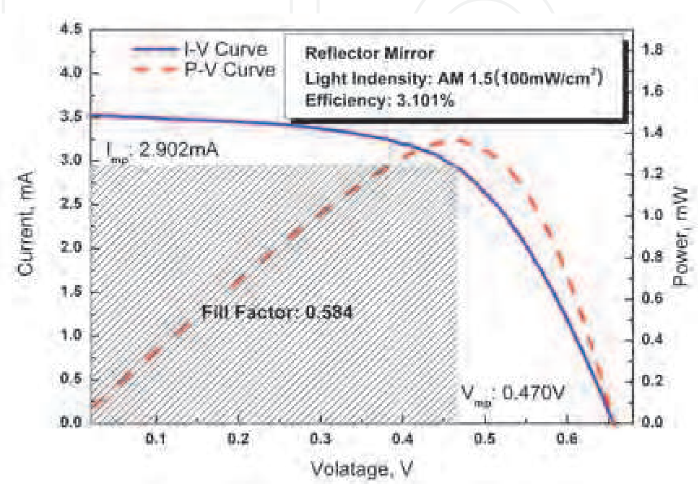

Fig. 21. I-V and P-V curve based on micro pyramid pattern reflector

3.4 Conclusions

This study machined micropatterned micro reflector and measured conversion efficiency of solar cell in order to increase efficiency of dye-sensitized solar cell. Its results are summarized as follows:

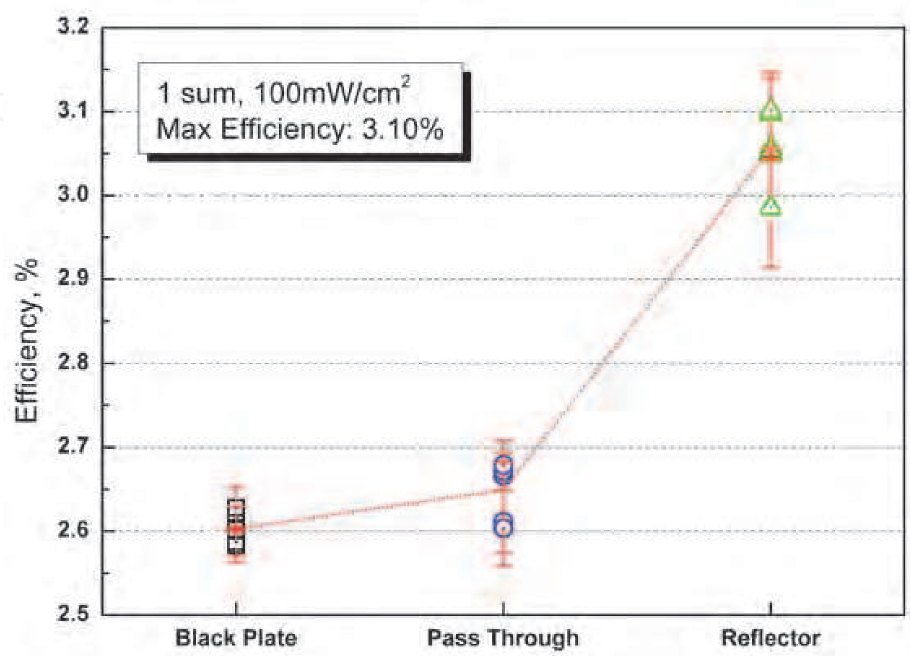

Fig. 22. Comparison of efficiency of different reflector

It was possible to get the optimal reflection angle 112.6° to increase conversion efficiency through reflector to collect lost light passing through dye-sensitized solar cell by performing light analysis.

When using reflector with pyramid shape, it was confirmed that it could get higher energy conversion efficiency by about 17% than a black plate

In case of micro pyramid reflector, maximized inclination to lengthen distance to meet dye layer of TiO_2 had maximized max power current (I_{mp}) and brought about entire efficiency improvement, different from vertical reflection.

4. Photovoltaic performance of Dye-sensitized solar cell by concentrating sunlight

One of method that can be improved efficiency of solar cell is concentrating light. Various factors influence the production of electricity from solar cells such as solar radiation, solar cell installation angle, direction, shade, solar cell module temperature. Among these, solar cell installation angle, direction, and shade have almost no influence on the system performance once the solar cell system is installed unless artificial external effects are given because they are determined when the solar cell system is designed and installed. After installation, the performance of a solar cell system varies greatly by the solar radiation reaching the module surface and the surface temperature. The higher the solar radiation, the higher the efficiency of the solar cell becomes. Due to the nature of the solar cell module, the power production increases in proportion to the solar radiation, and the power generation

increases as the surface temperature of the solar cell module increases. Therefore, we can improve the performance of solar cell modules by compulsorily increasing the solar cell module temperature through solar concentration.
This study intended to develop solar cell module that can maximize the efficiency of unit cells of dye-sensitized solar cell (DSSC) by maximizing solar concentration and minimizing solar loss while analyzing and improving the factors that influence the efficiency of DSSC.
In this study, and was concentrated by Fresnel lens. High temperature heat on concentration can decrease efficiency of solar cell so as cooling radiator was installed. Maximum concentrating ratio was 26 times of 1sun (2.6W/cm^2). When the solar energy of High density was illuminated on a DSC, It was confirmed that temperature and concentrating ratio affect efficiency of DSC.

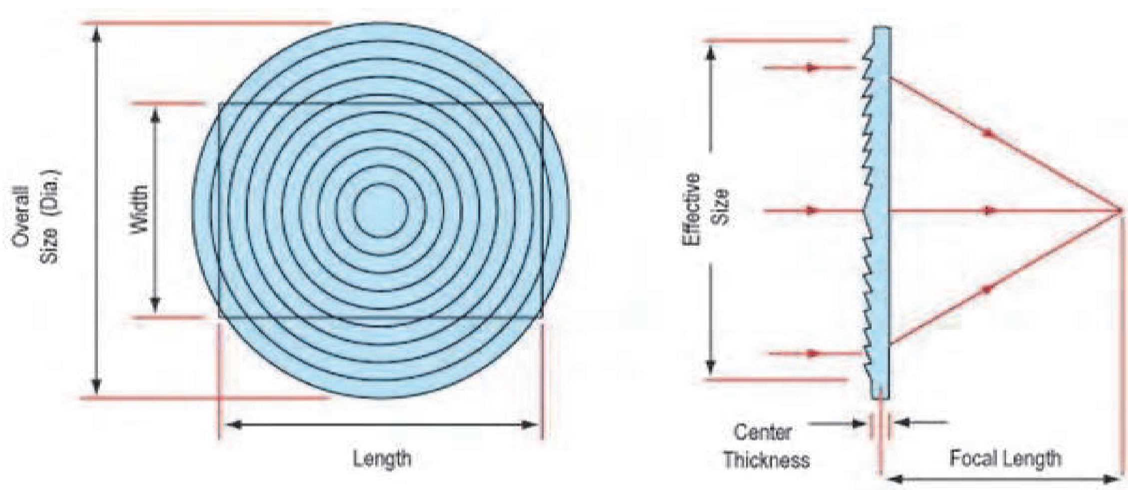

Fig. 23. Structure of Fresnel lens

Contents	Value
Grooves/Inch	100
Size H x L (inches)	5.0 x 5.0
Effective Size (inches)	Φ 4.0
Effective Focal Length (inches)	2.8
Center Thickness (inches)	0.06
Transmission (%)	92(wavelength 400~1100nm)

Table 2. Specifications of Fresnel lens

When high density light is illuminated in the DSC using concentrating lens, conversion efficiency is reached up to 16.11%. The enhancement in overall device efficiency is a result of increased open circuit potential and short circuit current. If coolant system is used, it can help guarantee of stable performance of a high efficiency of DSC at 45°C.

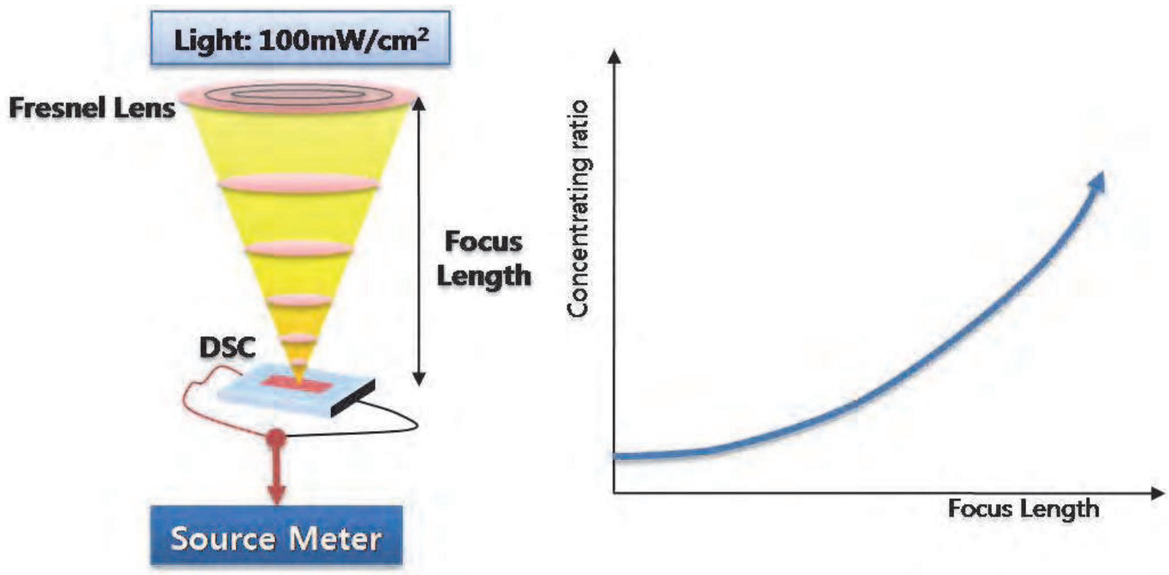

Fig. 24. Schematic of concentrating DSC

4.1 Evaluation of solar cell performance by changing temperature

High temperature is generated when solar energy is concentrated to improve energy conversion efficiency. Performance drops due to sealing problems such as the leakage and evaporation of electrolytes resulting from the changes in the volume of volatile electrolytes and the increase of vapour tension (Kim, 2007). To solve this problem, many efforts are being made to achieve performance reliability such as replacement of liquid electrolytes with solid electrolytes, development of new materials for sealing, and the performance of thermal stability tests (Fischer et al., 1997). Performance varies greatly by the surface temperature and the solar radiation that reaches the cell surface of a solar cell. The higher the solar radiation, the higher power production becomes, and the performance of a solar cell varies by surface temperature. In this study, the effects of the changing cell temperature on the efficiency of solar cells, and the optimum conditions for thermal stability in solar concentration and the production of solar cell module were investigated.

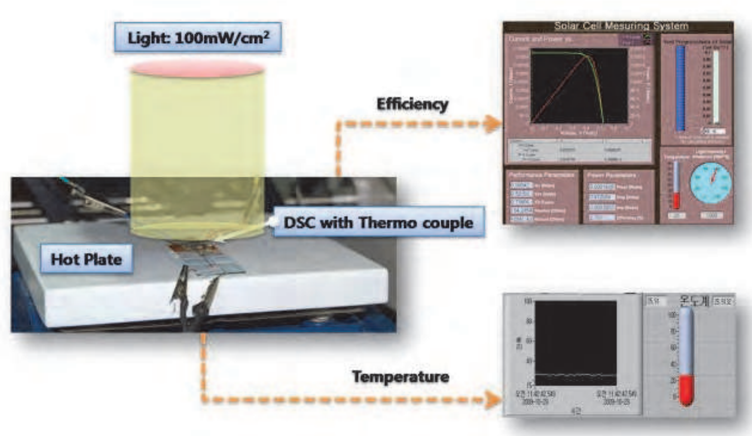

Fig. 25. Schematic design of measurements

Figure 25 shows a schematic diagram of a device for measuring the changes in the efficiency of DSSC according to changing temperature. A hot plate was used as a heat source, and a resin epoxy was used for sealing to prevent the leakage and evaporation of electrolytes due to exposure to high temperature. To examine the cell efficiency under changing temperature, a thermocouple for measuring temperature was attached to the DSSC. For this thermocouple, the K-type from Omega was used. The change in the efficiency of the solar cell was measured while the temperature was varied from 35°C to 65°C in 5°C steps.

4.2 Performance evaluation of the solar cell by solar concentration rate

The solar cell device was fabricated in such a way to obtain high efficiency by increasing the energy density through solar concentration. The lens for solar concentration was a Fresnel lens with the conventional curved surface of the lens replaced by concentric grooves, and fine patterns were formed on the thin, light plastic surface. Each groove has a refracting surface like a very small prism with a fixed focal distance and a low aberration. Because the lens is thin, it has a low loss from light absorption. A high groove density provides high image quality and a low groove density increases efficiency.

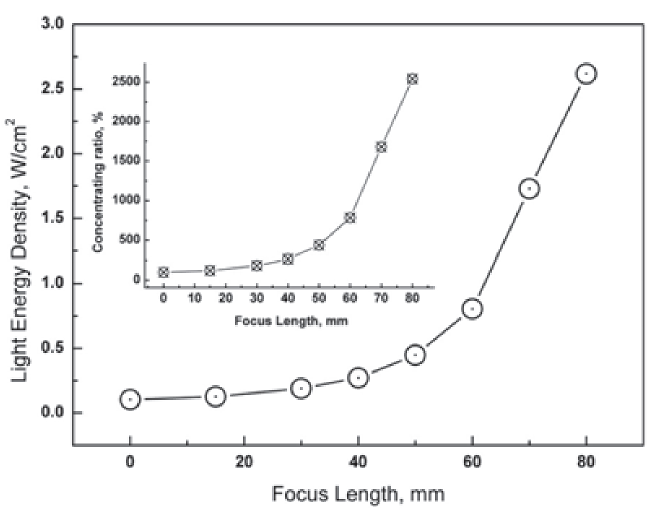

Fig. 26. Energy density due to focus length of Fresnel lens

The focal distances of the Fresnel lens were defined as 15, 30, 40, 50, 60, 70, and 80mm. A power meter was used to measure the concentrated energy density to determine the solar concentration rate for each focal distance. If was found that the energy density increased exponentially as the focal distance increased. As shown in Figure 26, the solar concentration rate at the highest focal distance was approx. 26 times (2.619W/cm^2) the 1sun (100mW/cm^2) condition.

4.3 Results

Figure 27 shows the results of the efficiency of the DSSC measured by different cell temperatures with the solar intensity of 1sun (AM 1.5, 100mW/cm^2). The cell efficiency increased as the cell temperature increased and abruptly dropped from 45°C.

Figure 28 shows the maximum output, maximum output current (I_{mp}) and voltage (V_{mp}) at various temperatures as percentages of the values at 35°C to determine the factors influencing cell efficiency and output. It shows I-V line diagrams comparing the changes of I_{SC} and V_{OC} at different cell temperature. I_{SC} increased as the cell temperature increased and dropped from 55°C while V_{OC} decreased as the temperature increased.

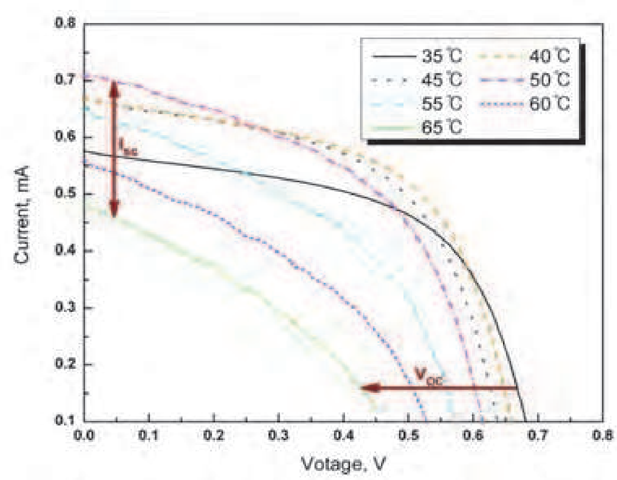

Fig. 27. Comparison of I-V curve due to temperature change

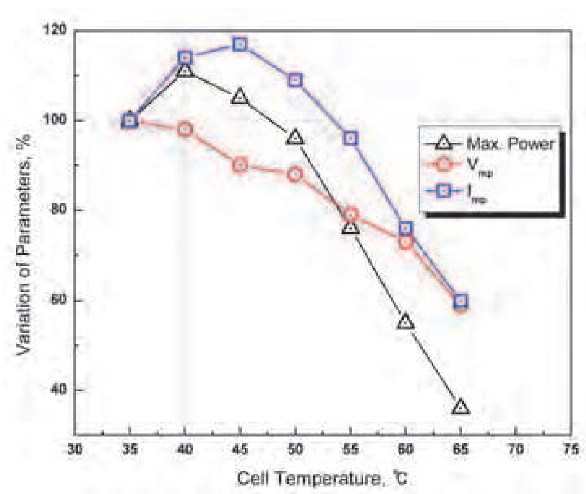

Fig. 28. Performance changes due to temperature change

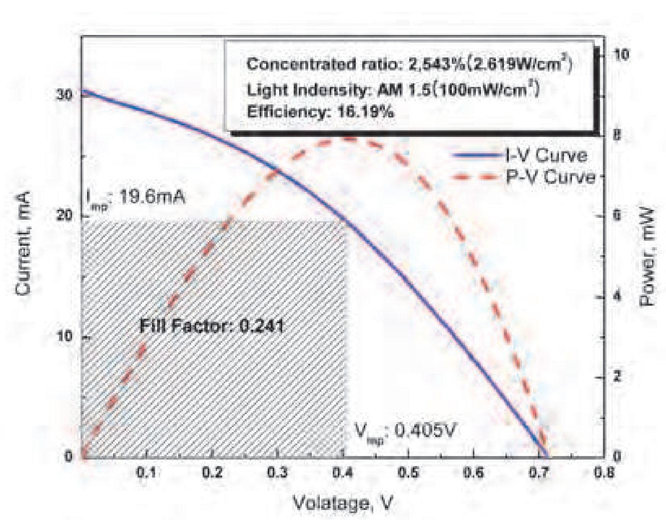

Fig. 29. I-V curves of DSC due to Focus length

The changing efficiency of the DSSC by solar concentration rate was measured at varying focal distances with the prepared lens and stage. Figure 29 shows the I-V line diagrams for each solar concentration rate. When the focal distance was 80mm and the solar concentration was at the maximum of 2,543%, the cell efficiency was 16.2%.

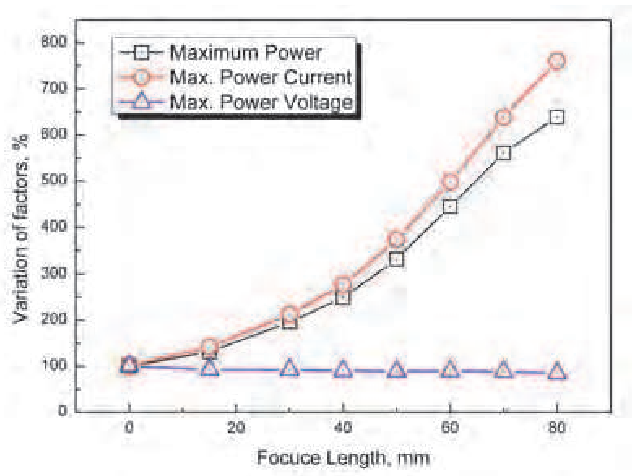

Fig. 30. Performance changes due to focus length

Figure 30 shows the maximum output for each focal distance and the voltage and current changes in percentages at the maximum output to determine the factors influencing efficiency improvement. The maximum output increased as the solar concentration rate increased, indicating cell efficiency improvement. It was found that the increase of current (I_{mp}) by solar concentration had a direct influence.

4.4 Conclusions

This study investigated the changes in efficiency when concentrated solar radiation with high energy density was applied to DSSC to determine the factors influencing efficiency.

- Imp increased as the cell temperature increased and dropped from 45°C while V_{mp} decreased as temperature increased.
- The efficiency of DSSC at changing temperatures was investigated when high heat was generated by solar concentration, and the highest efficiency was obtained at 45°C. As temperature increased over this value, the cell efficiency dropped sharply. Thus, a cooling device is essential when manufacturing a power generation system using solar concentration.
- The high energy density obtained by solar concentration increased the efficiency of DSSC by 6.4 times on average and up to 16.1% by absolute value. Because current density can be increased by solar concentration, it is possible to implement solar cells with a high output.

5. Concentrating system of Dye-sensitized solar cell with a heat exchanger

Conversion efficiency of solar cell is the key point for reducing price to manufacture products. The efficiency is expected to be improved by using the concentrator system, because lost energy density of concentrator system increase in proportion to quantity of concentration.

In this study, the conversion efficiency is expected to be improved by concentrating light which has high energy density through the concentrating lens. In this process, DSC will emit heat at high temperature and make defection like evaporation and leaks of an electrolyte. To protect this problem, we have discussed the way to ensure steady cells by developing the system available to return the heat of the high temperature.
Cell of temperature was maintained 30°C at 1sun(100mW/cm²) condition, Concentrated light density was 2.6W/cm² that is about 26suns. The cell is measured for 480 minutes because it is generally running for 8 hours during a day. On average, the conversion efficiency of the cell is 13. 24%. Finally we conform that the solar cell using concentration system with a heat exchange is available to steady and highly improve the conversion efficiency.

5.1 Concentrating system with a heat exchanger

The dye-sensitized solar cell with concentrated light generates high heat from concentrated light with high density and results in defections such as leakage of electrolyte, evaporation, etc. In order to prevent them, the researcher has installed a cooler under the solar cell and executed stability test. The stability test has a meaning to confirm efficiency change and ensure performance reliability of the cell when they have been exposed to the light for a long time. Figure 31 shows apparatus and conditions used for this test. Efficiencies have been acquired for a certain time period by keeping temperature of the cell at 30°C using the cooler and radiating light with 2.6W/cm² that is 25.4 times of the maximum light concentration under 1sun. Measurement time was 480 minutes considering that the number of hours when the solar cell can be operated during daytime on clean weather us 8 hours.

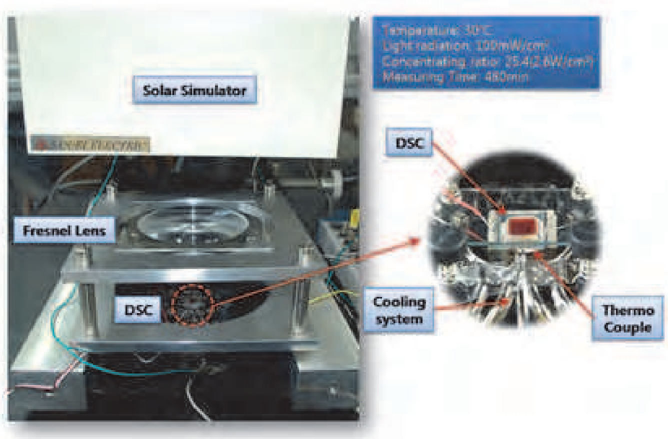

Fig. 31. Equipment for thermal stability test

5.2 Results

In order to measure efficiency change of the dye-sensitized solar cell upon change of light concentration coefficient, efficiencies have been measured according to focal distances using the prepared lens and stage. Figure 32 shows I-V curve of the solar cell upon light concentration coefficients. When the light concentration coefficient is a maximum of 2,543% at 80mm of focal distance, efficiency of the cell showed 16.2%.
Figure 33 shows efficiency changes of the dye-sensitized solar cell for 480 minutes in a graph. As the measurement was started and time passed, the efficiency was linearly reduced

and showed 11.5% after 480 minutes, reduced by 25.6% comparing to 15.4% of initial efficiency. It is considered that it could perform 13.2% of average efficiency over the entire time period. Consequently, it is possible to realize a stable and high efficient solar cell with light concentration utilizing the cooler.

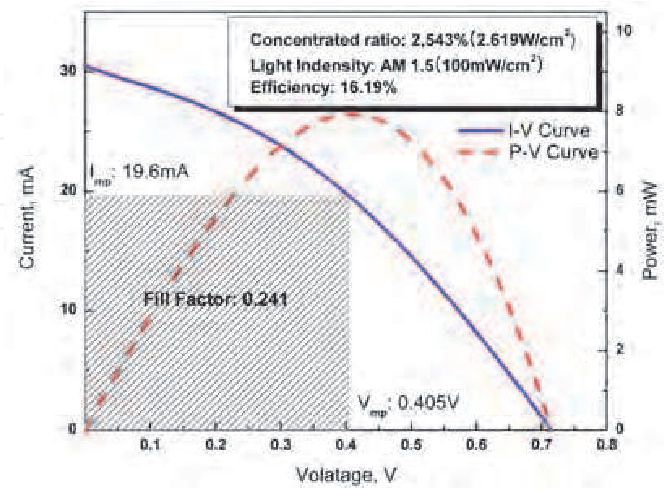

Fig. 32. I-V curves of DSC on Focus length 80mm

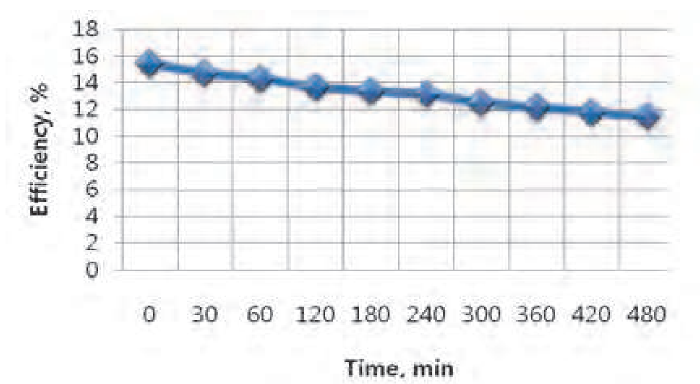

Fig. 33. Efficiency change of DSC due to time

5.3 Conclusion

When concentrating light through the Fresnel lens that has less light loss with thinner than normal lens and may increase energy density with small aberration against focus, it was possible to confirm a maximum light concentration coefficient at 80mm of focal distance.

When keeping a certain temperature (about 30°C) using the cooler, it was possible to get average 13.2% efficiency for 8 hours using the condenser lens. This shows that it would be possible to realize the high efficient dye-sensitized solar cell by making light concentration and cooling system in a module.

Light concentration is mostly advantageous as a practical technology of the high efficient dye-sensitized solar cell. In addition, it is possible to increase comprehensive energy use rate by progressing power generation and heating at the same time as a cogeneration pattern using the high heat generated from light concentration. This has applied light concentration and cooling on the basis of a single cell, but it would be possible to get the higher efficiency from fabrication cost per unit area and operation of the circulation system such as motor, etc. if it will be extended to a large area in a form of a power plant.

6. Acknowledgment

This chapter is composed to be based on my thesis of doctorate and proceedings of conferences.

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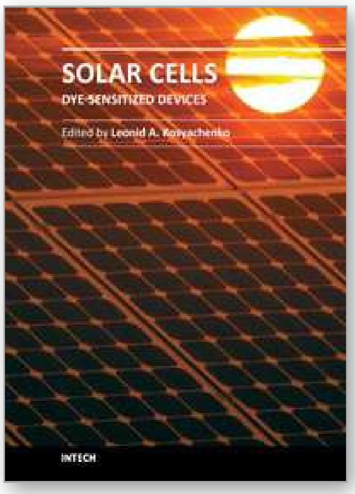

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The second book of the four-volume edition of "Solar cells" is devoted to dye-sensitized solar cells (DSSCs), which are considered to be extremely promising because they are made of low-cost materials with simple inexpensive manufacturing procedures and can be engineered into flexible sheets. DSSCs are emerged as a truly new class of energy conversion devices, which are representatives of the third generation solar technology. Mechanism of conversion of solar energy into electricity in these devices is quite peculiar. The achieved energy conversion efficiency in DSSCs is low, however, it has improved quickly in the last years. It is believed that DSSCs are still at the start of their development stage and will take a worthy place in the large-scale production for the future.

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