Master's Thesis

# Highly transparent silicon solar cell with flexibility

Won-Jin Park

Department of Materials Science and Engineering

Graduate School of UNIST

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ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

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Approved by

_______________________

Advisor

Kyoung-Jin Choi

# Highly transparent silicon solar cell with flexibility

Won-Jin Park

This certifies that the thesis/dissertation of Won-Jin Park is approved.

7.5.2019

signature

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Advisor: Kyoung-Jin Choi

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Myoung-Hoon Song

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Hye-sung Park

# Abstract

The BIPV system has recently been actively studied as a new energy source with the development of solar cells. However, the third generation solar cells mainly used in BIPV systems are difficult to apply to full-scale BIPV systems due to problems such as selective solar light absorption, small active area, inherent color of organic materials, and low stability that are not yet commercialized have. In order to solve these problems, studies are being conducted to apply currently commercialized silicon solar cells to BIPV system.

There is no problem in applying the silicon solar cell to the outer wall of the building, but there is a limitation in applying it to the glass window due to the weight problem of the silicon solar cell panel and the appearance of the unsuitable silicon solar cell. Therefore, the thickness reduction and transparency of the silicon should be studied.

In this experiment, I reduced the thickness of the silicon wafer and drilled a fine hole in the solar cell to make a transparent silicon solar cell. Transparent silicon solar cells have not suffered a significant loss in efficiency compared to flat silicon solar cells, and the introduction of additional processes has the potential to increase the efficiency of transparent silicon solar cells beyond current levels.

# Contents

# Figure contents

# Table contents

# I. Introduction

Depletion of natural resources such as petroleum and environmental pollution are our first priority, and many efforts are still being made to develop environmentally friendly energy sources. Among them, solar energy is being studied indefinitely because it is an energy source that can generate infinitely and does not pollute the environment in the process of production. Figure 1 shows the current use of energy on earth[1-2]. As you can see in the figure, the most energy-consuming space in Seoul and the US is a "building". If this building itself becomes an energy source, its value will be enormous. To realize this idea, a concept called BIPV(Building Intergrated PhotoVoltaic) system was introduced that attaches a solar panel that can generate solar energy to a building and makes the building itself a source of energy. Figure 2 shows buildings with representative BIPV technology around the world.

Solar cells can be classified into three types according to generation. The first-generation silicon solar cell is the most stable and has become the most commercially available in the world because it can maintain a steady high efficiency for a relatively long period of time. In order to maximize the energy production of the first generation silicon solar cell, a large space is inevitably required. However, the Republic of Korea is mainly composed of mountains, and there is not enough space for installing silicon solar cells in mountains. Cutting down trees to install solar cells in the mountains should not be able to cause another environmental problem. In addition, silicon solar cells can not be made to look beautiful due to the nature of their structure, and they should always be seen only in blue. In addition, silicon solar panels weighing several tens of kilograms can be problematic for applying heavy weight to BIPV. Third generation solar cells are made mainly of organic materials. Third generation organic solar cells have a relatively short lifetime compared to first generation silicon solar cells, and toxic materials are often used in the fabrication process, which may lead to new environmental problems and require caution in the process. However, organic solar cells still have a great deal of effort to be applied to BIPV systems because they have advantages in process cost and production cost compared to conventional silicon solar cells, they are lightweight and superior in appearance to silicon solar cells. However, it is true that there are some limitations in applying the third generation solar cell to the BIPV system for window.

In order to apply transparent solar cells to BIPV systems for windows, it is necessary to examine the transmittance of window characteristics in more detail. Figure 3 shows the relationship between window glass transmittance and energy consumption improvement[3]. As you can see from the figure, if the glass's transmittance is too low or too high, it is not good for the energy efficiency of the building. If the transmission of the glass is too high, the amount of sunlight entering the building increases and solar energy radiation becomes active. Therefore, additional cooling energy is required to keep the inside of the building. Conversely, if the glass permeability is too low, the amount of sunlight coming in the building is significantly reduced and solar energy radiation is not good. Therefore, they require additional heating energy to keep the building warm. Taking all of these points into consideration, I can conclude that the glass used in buildings must maintain a 50-70% transmission.

Table 1 shows the previous transparent solar cells that have been studied[4-10]. As can be seen in the table, all of the transparent solar cells studied have been based on the third generation organic solar cell. The efficiencies of these transparent solar cells are mostly not bad, but their transmittance is insufficient to apply to window BIPV, and their active area is quite small. Figure 4 shows the transmittance characteristic of organic solar cell[11]. As can be seen in the figure, the previous transparent solar cells have a very strong characteristic of transmitting light at a specific wavelength, which helps the solar cell to give a unique color. For example, an organic transparent solar cell shows a considerable amount of light passing through the red region of the visible light, which indicates that the transparent solar cell has a red-based color as a whole. Although building windows use a partially colored glass window as aesthetic point, as a whole, the windows must be transparent to function properly. Thus, it can be concluded that these organic solar cells are unsuitable for application to window BIPV system.

After discovering that organic solar cells are not suitable for BIPV, I once again recalled silicon solar cells for application to BIPV. In fact, silicon solar cells are already being developed as the most suitable solar cells for BIPV. Looking back at Figure 2, we can see that the exterior walls of the BIPV building are all made up of silicon solar cells. However, all of the BIPV technologies used here are applied to the exterior walls of the building, and can not be applied to the glass windows of buildings. First of all, silicon is not transparent, so when you attach it to a building's window, the window can not cover the outside scenery. Secondly, since the weight of the silicon solar cell panel is heavy, when the panel is attached to the glass window, the glass window frame may be damaged. To solve these problems, it is concluded that silicon solar cells should be lightweight and transparent. So how can we make silicon light and transparent?

The idea is very simple, but obvious. By reducing the wafer thickness, the weight of the silicon solar cell can be reduced, and by making holes in the silicon can be made to make the solar cell transparent. If there is a hole in the silicon, the object behind the silicon will be visible through the hole, and if the hole size increases or the number of holes increases infinitely, the transparency of the silicon will become even higher. A simple picture to help you understand this idea is shown in Figure 5.

In this experiment, I fabricated a solar cell with a wafer of thin silicon thickness, and drilled a fine hole in the silicon solar cell to produce a transparent solar cell.

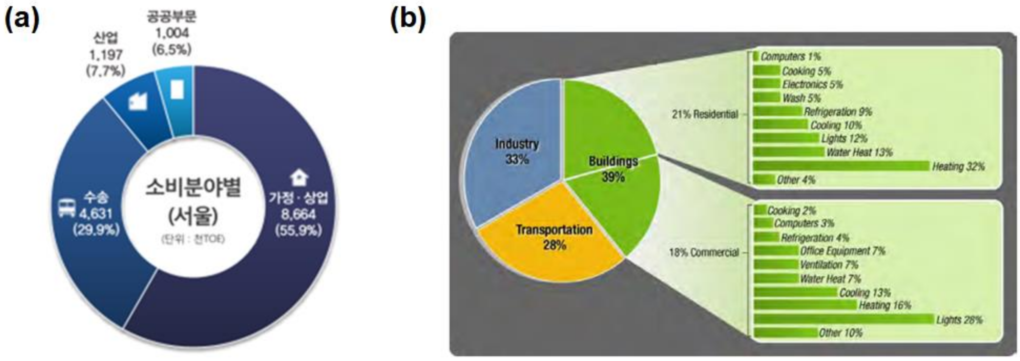
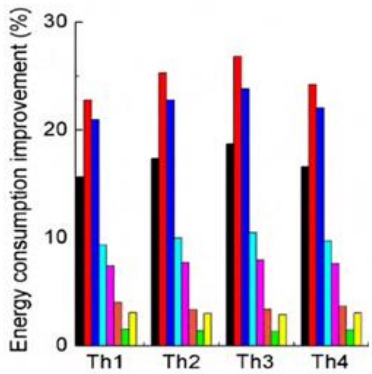



Fig.1. Energy consuming area of (a) Seoul, South Korea and (b) United States


Fig.2. Representative BIPV buildings




| Sample | visible transmittance/% |
|---|---|
| Thermochromic 1 ($VO_2$) | 78 |
| Thermochromic 2 ($VO_2$ + gold) | 56 |
| Thermochromic 3 ($VO_2$ + TOAB) | 61 |
| Thermochromic 4 ($VO_2$ + gold + TOAB) | 77 |

Fig.3. Relationship between window glass transmittance and energy consumption improvement.

| Ref No. | Solar cell | Transmittance (%) | Active area ($mm^2$) | PCE (%) |
|---|---|---|---|---|
| [4] | Quantum Dot | 24% | 7 | 5.4 |
| [5] | Perovskite | 30% | 12 | 6.41 |
| [6] | Quantum Dot | 32% | 7 | 2.04 |
| [7] | Polymer solar cell | 35% | 10.08 | 4.25 |
| [8] | Electrophoretic | 45% | 25 | 7.11 |
| [9] | solution process | 49% | 10 | 3.82 |
| [10] | Near-Infrared OPV | 55% | 1.2 | 1.7 |

Table 1. Previous transparent solar cells.

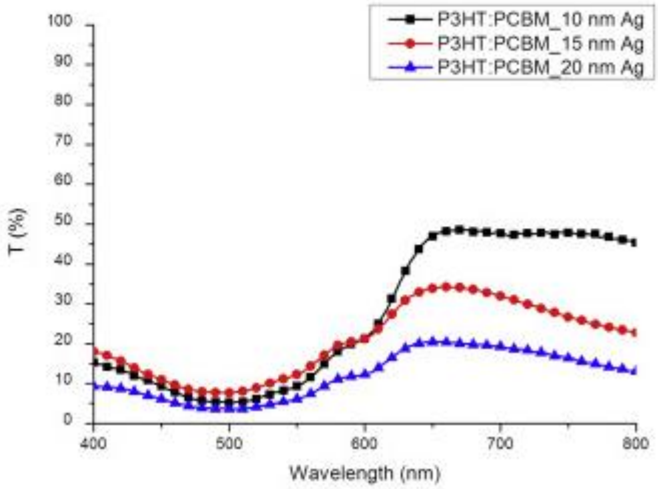




Fig.4. Transmittane spectra of organic transparent solar cell.

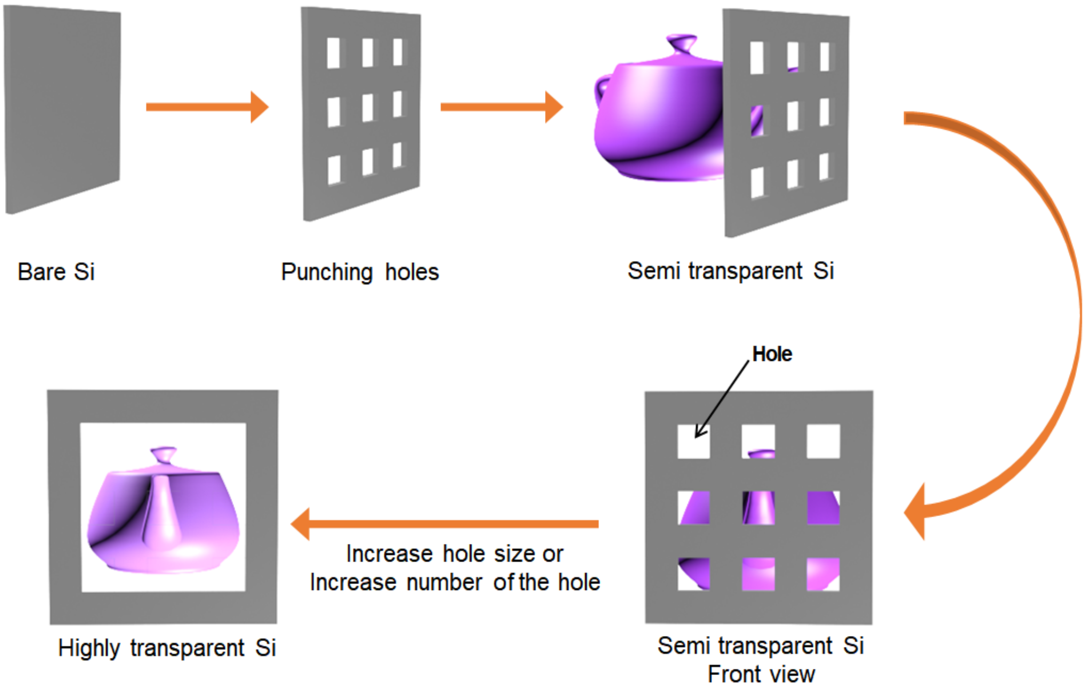



Fig.5. The basic idea of this experiment.

# II. Background

## 2.1 Principle

Solar cells are semiconductor devices that convert sunlight into electrical energy. The most basic silicon solar cell has a form of junction of p-type semiconductor and n-type semiconductor. On the front side, there is an antireflection film which reduces the reflection of sunlight so that more light enters into the solar cell.

A brief description of the driving principle of a solar cell can be expressed as absorption of light energy, generation of electron-hole pairs, separation of electron-hole pairs, collection of electrons and holes with front and rear electrodes, and generation of electric energy.

When the light energy incident from the sun is larger than the band gap of the solar cell, electrons enter the conduction band from the valence band by the incident light energy inside the solar cell, and the electron-hole pair is created.

The resulting electron-hole pair is separated from the electrons by the n-type semiconductor and the holes by the p-type semiconductor due to the electric field formed by the depletion region at the p-n junction.

The separated electrons and holes are collected by the electrodes located on the front and rear sides of the solar cell, and generate a photovoltaic effect. When the electrons flow through the outer conductor, they act as an energy source.

Simple solar cell structure is shown in Figure 6.

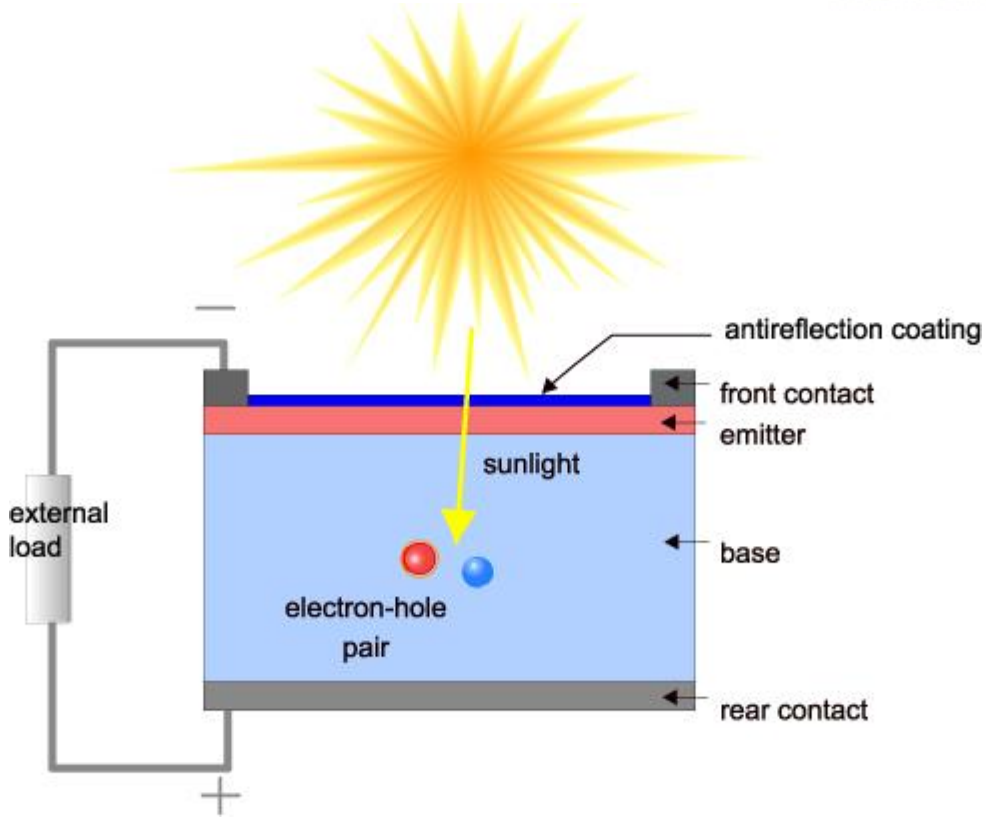



Fig.6. Basic principle of solar cell

## 2.2 Solar cell parameters

The solar cell is a large area diode, and the current-voltage curve of the solar cell shifts the diode current-voltage curve in the dark state downward by the photo generation current $I_L$.

The diode equation is as follows.

$$I = I_d - I_L = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - I_L$$

**Short circuit current, $I_{sc}$**

The short circuit current means the current flowing when the voltage across the solar cell is zero. In short, short circuit current means the maximum current value that can be obtained from the solar cell.

The short circuit current of the solar cell is expressed by the following equation.

$$I_{sc} = \int_0^{\infty} J_{sc}(\lambda)d\lambda$$

$$\simeq \int_{0.3\mu m}^{\lambda_0} J_{sc}(\lambda)d\lambda = \int_{0.3\mu m}^{\lambda_0} \big(1 - R(\lambda)\big)qF(\lambda)\eta$$

$\lambda$= Wavelength of incident light

R($\lambda$) : Reflectance at surface

F($\lambda$) : The number of photons in the range of wavelength $\lambda \sim \lambda + d\lambda$ in the solar spectrum

The short circuit current is affected by the active area of the solar cell, the intensity of the incident light source, the optical spectrum, the absorption and reflection of the sunlight, and the collection probability.

The short circuit current is different for each solar cell area. To solve the area dependency, the $I_{sc}$ value is divided by the active area of the solar cell and expressed as the short-circuit current density, $J_{sc}$ value.

**Open circuit voltage, $V_{oc}$**

Open-circuit voltage refers to the voltage appearing across the solar cell when the solar cell current is zero. In other words, the open-circuit voltage means the maximum voltage that can be obtained from the solar cell. Since $V_{oc}$ is the voltage when the current is 0, if I=0 and $I_L$=$I_{sc}$are substituted,

$$V_{oc} = \frac{nkT}{q}\ln(\frac{I_{sc}}{I_0} + 1)$$

The smaller the leakage current is, the larger the band gap of the solar cell becomes, the larger the $V_{oc}$ becomes. $V_{oc}$ can be greatly increased due to back surface field (BSF) characteristics formed by a rear Al electrode in a silicon solar cell.

As the energy band gap increases, the $V_{oc}$ value increases, but the area absorbed in the solar spectrum decreases and the photo-generated current decreases. In general, the energy band gap that achieves the maximum efficiency is known to be 1.4 to 1.5 eV.

**Fill Factor, FF**

The fill factor is the factor that determines the maximum power of the solar cell and is defined as the ratio of the output to the product of $V_{oc}$ and Isc as shown in the following equation. This is the area of the largest rectangle that can be filled in the I-V curve. Fill Factor shows the approximation of Imax and Vmax to $I_{sc}$ and $V_{oc}$ in the I-V curve.

$$\mathrm{FF} = \frac{I_{max} \times V_{max}}{I_{sc} \times V_{oc}} = \frac{V_{max}}{V_{oc}}\left[1 - \frac{\exp\left(\frac{qV_{max}}{nkT}\right) - 1}{\exp\left(\frac{qV_{oc}}{nkT}\right) - 1}\right]$$

The fill factor is influenced by the ideal coefficient n, which is the degree to which the diode deviates from the ideal diode characteristic, and the series and shunt resistances.

**Power Conversion Efficiency, Effi.(η)**

Power Conversion Efficiency(PCE), the most important and meaningful indicator of solar cells, is the ratio of the output energy to the energy input from the sun.

Power Conversion Efficiency is generally influenced by incident light spectrum, light intensity, and temperature. Therefore, the conversion efficiency is generally measured at 25℃ and AM 1.5.

$$\eta = \frac{P_{max}}{P_{input}} = \frac{I_{max} \times V_{max}}{P_{input}} = \frac{I_{sc} \times V_{oc} \times FF}{P_{input}}$$

**Series resistance, $R_s$**

Series resistance is caused by the resistance of between the emitter and base, the resistance between the metal electrode and the emitter, the resistance between the base and the resistance of the metal electrode. The larger the series resistance, the more the FF will be affected.

**Shunt resistance, $R_{sh}$**

Shunt resistance occurs mainly when there are many defects in the manufacturing process of the solar cell or when the electrode penetrates the emitter layer. The lower the shunt resistance, the greater the leakage current, which reduces the photo generation current and voltage.

# III. Experimental

## 3.1 Traditional Silicon solar cell

First, I fabricate basic silicon solar cells and optimized their efficiency.

- Wafer preparation

In this experiment, P type wafers (resistivity 1-5 ohms) with thicknesses of 100 micrometers and 300 micrometers were used. The wafer is cut into a suitable size (220 mm x 220 mm), then subjected to standard RCA cleaning, acetone and IPA organic cleaning, and then washed thoroughly in flowing DI water.

- Emitter formation

P507 Spin On Dopant (SOD) was used for emitter formation. First, the backside of the wafer was protected with $SiO_2$ for selective emitter formation, and then P507 SOD is spin coated with spin coater. After SOD coating, the emitter formed by Rapid Thermal Annealing (RTA) process. Phosphorous Rich Layer (PRL) and Phosphorous Silicate Glass (PSG) layer was removed by HF after the emitter is formed.

- Active area definition

To define the active area, I use a photolithography method, and then I use a reactive ion etching (RIE) equipment to sufficiently etch the area outside the active area so that only the emitter area within the active area remains. The remaining PR after RIE etching is lifted off in acetone.

- Electrode formation

In order to form the electrode, the front electrode pattern is formed by using the photolithography method, and Ag is deposited by the ion beam deposition. After deposition, the wafer is immersed in acetone and lift off.

- Front surface passivation

The solar cell formed up to the electrode uses the PECVD (Plasma Enhanced Chemical Vapor Deposition) equipment to deposit the $Si_3N_4$ layer. The $Si_3N_4$ layer serves not only as a front passivation but also as an antireflection film.

In this way, the basic thin-film silicon solar cell was processed. The next step was optimization of the silicon solar cell process. First, I optimized the front electrode by changing the electrode design considering the shadow loss of the front electrode of the solar cell. Secondly, I have optimized the solar cell emitter condition. The results are shown in Figure S1 and Figure S2. First, when using a electrode pattern with a small coverage, the amount of sunlight absorbed into the active area was increased, so that a higher $J_{sc}$ value was obtained, but the $V_{oc}$ and FF values were not significantly different. Therefore, the electrode pattern with a small coverage was used to fabricate a solar cell with a higher efficiency. Second, I changed the formation conditions of the emitter by changing the temperature of RTA. When the sheet resistance is 100Ω/□ after forming the emitter, the efficiency of the solar cell is the hightest. After optimizing these solar cell conditions sufficiently, I proceeded to the next step.

## 3.2 Transparent Silicon solar cell

After this basic silicon solar cell process, I thought about punching holes in solar cells to make transparent silicon solar cells. I have tried various ways to drill a hole in a solar cell.

First, I tried a method of etching by using Negative Photo Resist (PR) (AZ N-lof) as an etching mask. With this method, it is easy to use because it can be etched after the pattern is formed on the formed solar cell. However, unlike the conventional process of etching only a thin thickness, this time, the PR does not protect the silicon in the process of etching the deep thickness, and a part is broken. In addition, since the remaining PR after etching has received too much plasma damage, the lift off is not easy, and when the PR-Asher equipment is used, the Ag electrode remaining in the $Si_3N_4$ layer used as a protective film is oxidized there was.

Second, a method of using Al as a BSF film and then using an Al-BSF layer as an etching mask has been tried. This method has an advantage in that the efficiency of the transparent solar cell after fabrication is improved because etching is attempted in a state where the efficiency of the cell is greatly increased due to the back surface field effect. However, when the Al-BSF alloy was also used as an etching mask, the plasma was not able to withstand damage and the sample was broken.

Third, I tried to use a pure Al as an etching mask by using an etching pattern before the Al-BSF. Using this method, a solar cell with an Al-back surface filed can be formed. However, since the adhesion property of Al is not good, there arises a disadvantage that Al is peeled off when the etching pattern is formed and then developed. In addition, even if etching is performed using Al as an etching mask by finding another method, it is judged that making an emitter using SOD on the silicon is difficult due to a shunt problem.

Finally, I used Cr(Chromium), one of the most commonly used methods in the DRIE process, as an etching mask. Cr is well known as one of the most useful etching masks in DRIE because of its good adhesion and hardness. Using this method has the advantage that it can be etched most successfully, although the procedure is a bit more complicated than the methods mentioned above. A photolithography method was used to fabricate an etching mask on the basic silicon solar cell fabricated by the previous experiment. Cover the area to be etched with positive Photo Resist (AZ 5214) and deposit Cr by e-beam evaporation. After lift-off, the sample is placed in the DRIE and the etching proceeds. As a result of the experiment, it was confirmed that the etching was successful. A detailed description of the etching conditions will be discussed again in the experimental results. The etched samples cleaned by acetone and IPA, and the remaining Cr etching mask was removed by Cr etchant.

After Si etching process, the Ag was obliquely deposited by e-beam evaporation to make the silicon solar cell back electrode.

The overall process of the experiment is shown in Figure 7-8.

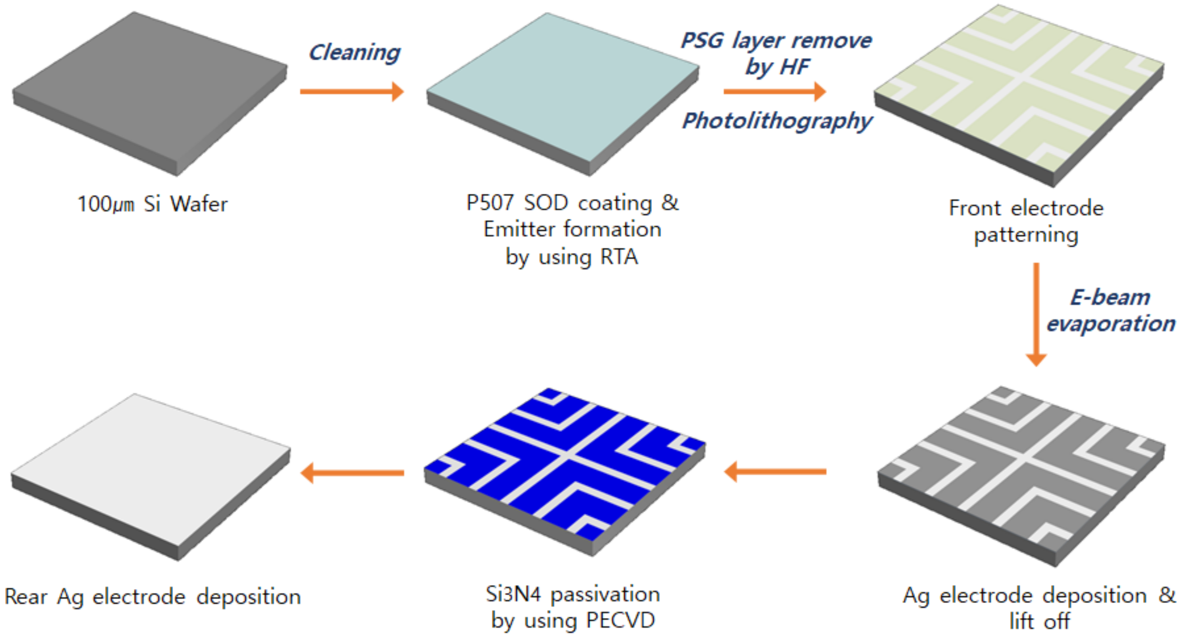



Fig.7. Basic solar cell fabrication process.

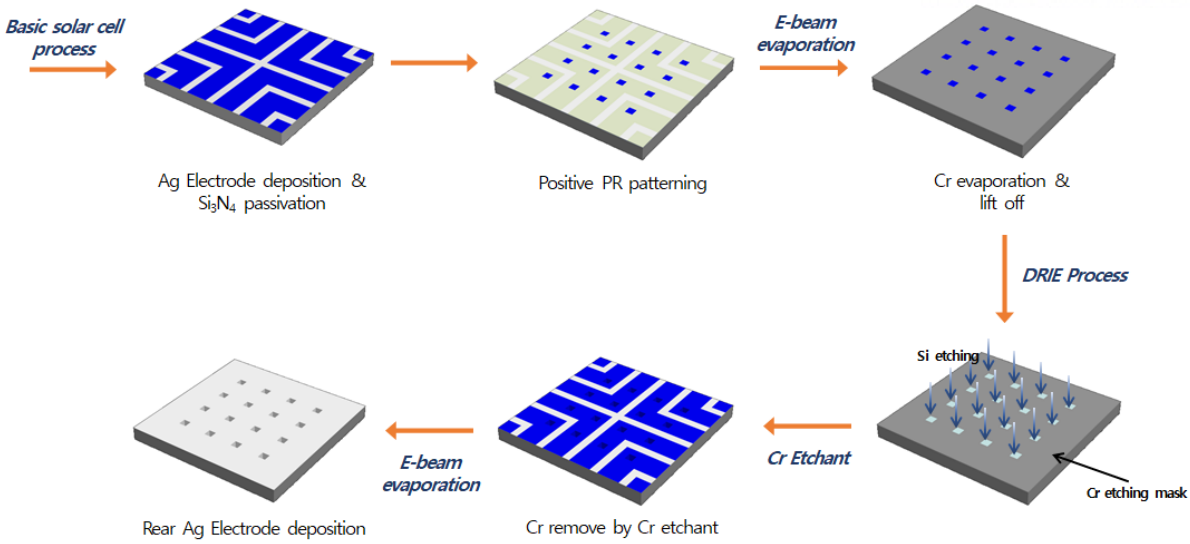



Fig.8. Transparent silicon solar cell fabrication process.

# IV. Results & Discussion

## 4.1 Optical property

In order to determine the thickness of the wafer to be used in the experiment, we first analyzed the absorption depth of the solar cell and the absorption effect of silicon[12]. Figure 9(a) shows that the thinner the silicon wafer thickness, the smaller the light in the longer wavelength range that silicon can absorb. For example, a silicon wafer with a thickness of 100 micrometers may completely absorb light of a wavelength of about 980 nm, and the subsequent light can not be completely absorbed, and a 500 micrometer thick silicon wafer seems to be able to fully absorb light up to a wavelength of about 1020 nm, and the subsequent light is completely absorptive. To clarify this, I calculated the AM 1.5G spectra as a reference and analyzed the absorbance of wafer thicknesses of 100, 300, and 525 micrometers. In the case of silicon metal, Since the reflectance in the wavelength range in which silicon can absorb light is close to 0, the absorbance was measured by subtracting the reflectance from 1. The reflectivity of the corresponding silicon is shown in Figgure S3, and the absorption spectrum according to the wafer thickness calculated based on it is shown in Figure 9(b). As you can see in Figure 9(b), the absorption spectrum of silicon shows that all light is absorbed similarly to silicon in regions before 980 nm, regardless of wafer thickness. However, if the thickness of the wafer is thin, it can be confirmed that the degree of absorption in the long wavelength region is slightly lowered. However, the difference in absorption is very small and can be ignored. A more detailed absorption spectrum and area comparison with AM 1.5G is shown in Figure S4. This has led to the conclusion that silicon can absorb almost the same light regardless of the wafer thickness.

Next, in order to check the performance of the silicon solar cells with different thicknesses, simulation was carried out through the PC1D simulation program, and a silicon solar cell was fabricated based on the simulations. The results are shown in Figure. Figure 10 shows that the simulated and actual results are almost similar. It was concluded earlier that the amount of light absorbed is almost constant regardless of the thickness of the silicon wafer. However, The simulation result and the actual result show that the Jsc value of the solar cell decreases sharply when the thickness becomes thinner than a certain level. This is attributed to the bulk recombination effect of the solar cell. Based on the simulation results and actual results, we determined the thickness suitable for making transparent solar cells. Because the 525 micrometer thick is not significantly different from 300 micrometers, we decided not to use the 525 micrometer thick wafer for silicon etching. In addition, 10 micrometer thick wafers were considered to be unsuitable for making transparent solar cells because their efficiency was too low when they were made from solar cells and high handling was required in actual processes. Therefore, in this experiment, I decided to make solar cells with 300 micrometer and 100 micrometer thick silicon wafers.

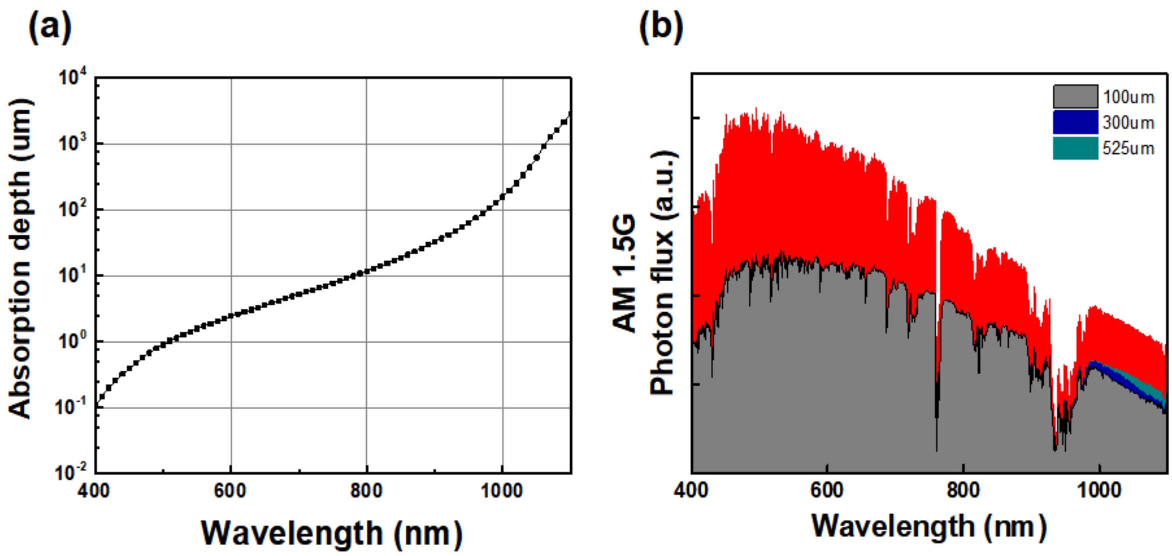



Fig.9. (a) Absorption depth of Si and (b) Absorption spectra of Si by wafer thickness

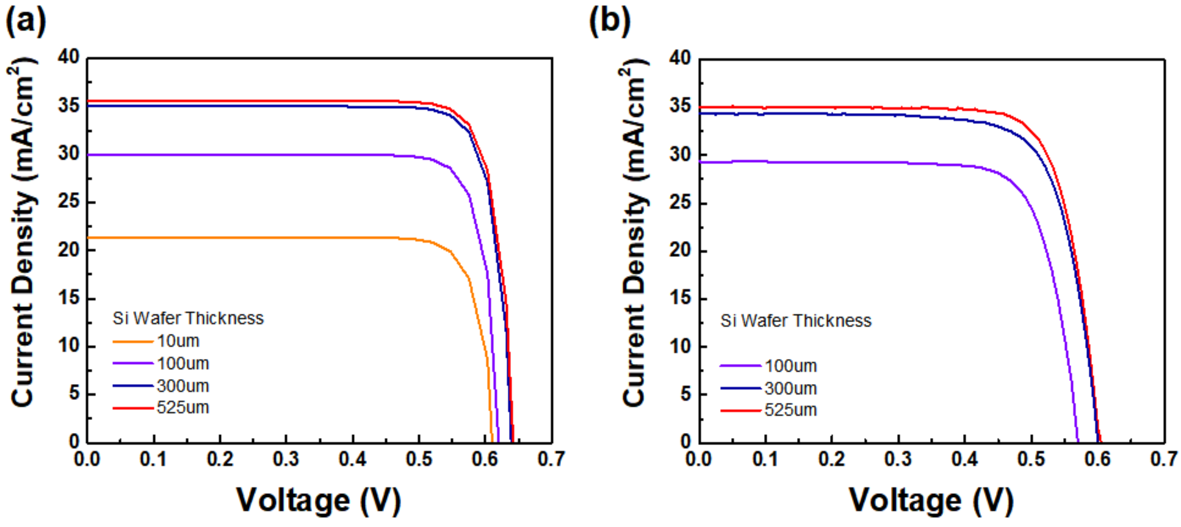



Fig.10. Simulated and actual fabrication of silicon solar cell by wafer thickness.

## 4.2 Solar cell property

Figure 11 is a SEM image of a cross-section of a sample with 100 micrometer and 300 micrometer wafers etched in DRIE. Because I had to etch fairly thick wafers, I used the Bosch process. Figure S5 shows the simple process of the Bosch process.

As such, the bosch process etches silicon as the $C_4F_8$ gas passivates the silicon and the $SF_6$ gas etches the silicon alternately. Figure S5 illustrates these process[13]. In this experiment, $C_4F_8$ gas was deposited for an amount of 150 sccm for 0.8s and SF6 gas was etched for 300 sccm for 6.4s. Looking again at Figure 10, the time required to etch 100 micrometers thick was 40 minutes, and the time required to etch 300 micrometers was 100 minutes. Looking closer at the picture, there were traces of damage to the surface of the silicon. In addition, 300 micrometer silicon has been exposed to etch for too long, resulting in more damage and eventually fragile of the silicon.

Solar cells show a form of a large diode when there is no light. When a solar cell starts to produce electricity by receiving light, the diode curve of the solar cell is shifted by the production power of light ($I_L$), and the expression at that time is expressed as follows.

$$I = I_d - I_L = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - I_L$$

Here, $I_0$ is expressed as dark saturation current or leakage current. If the expression is represented at the Voc point (ie, $I = 0,\ I_0 = I_{sc}$), the equation can be summarized as follows.

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_{sc}}{I_0} + 1\right)$$

We can see here that the $V_{oc}$ of the solar cell decreases as the $I_0$ value (dark saturation current) increases.

Figure 12 shows the dark J-V curve of the etched silicon. As can be seen in the figure, the dark saturation currents of 300 micrometers and 100 micrometers are quite high, especially the dark saturation current of 300 micrometers. This means that when the 300 micrometer solar cell is etched, the decrease of the $V_{oc}$ is increased, and the leakage current is increased, which may seriously degrade the cell efficiency. So, I decided to make a transparent silicon solar cell with 100 micrometer wafer thickness in this experiment.

Figure 13 shows the etching pattern used for silicon etching. Two patterns were used for this etching, one with a size of 200 micrometer and an opening area of about 80%. The other one was a pattern with a small size of 80 micrometer and its opening area was about 55%. Figure 14 shows the appearance and transmission spectra of a silicon solar cell etched using the pattern. As can be seen in the figure, the transmittance in the visible region was about 60% for the large hole with large pattern size, and the transmittance in the visible region was about 45% for the small hole with small pattern size. It can be confirmed that this value is much larger than 0.03%, which is the reflectivity of a general silicon wafer. In addition, the solar cell active area in this process was set at 250mm$^2$, which is much larger than the other previous transparent solar cell areas described earlier. In conclusion, it was confirmed that the silicon transparent solar cell formed under these conditions shows a suitable transmittance for the window BIPV and a sufficiently wide active area.

Figure 15 shows the J-V curve of a transparent silicon solar cell fabricated using the above etching conditions. The J-V curve shows that the power conversion efficiency of the transparent silicon solar cell is 1.65% in the large hole and 3.47% in the small hole. As can be seen from the J-V curve, the series resistance of the two transparent silicon solar cells was measured to be very large, and it was confirmed that the reduction of the FF and the reduction of the power conversion efficiency occurred. To get a closer look at this cause, I looked at the SEM image of the cross section in more detail. Figure 16 shows a cross section of a sidewall of a 100 micrometer etched wafer. As you can see in the figure, you can see that the sidewall is severely broken. This makes it possible to estimate that the etching conditions give a lot of etching damage to the silicon cross-section, thereby decreasing the efficiency of the solar cell.

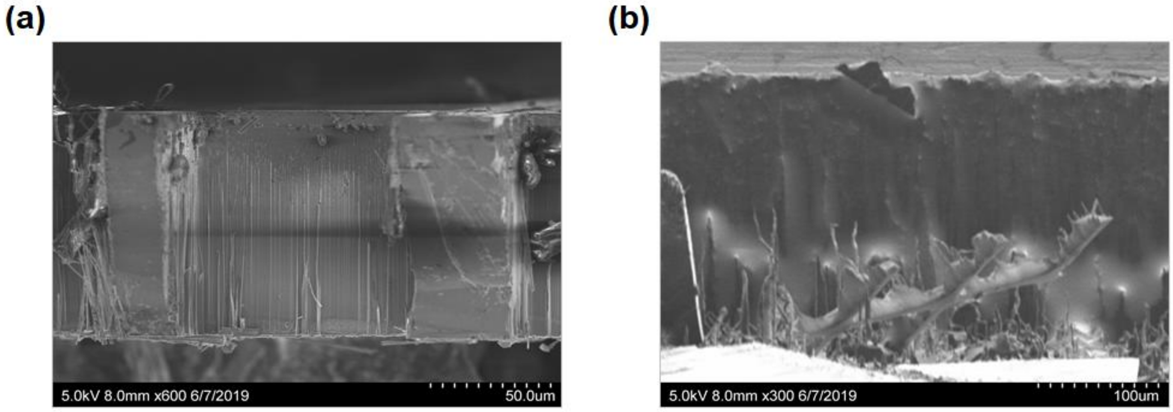



Fig.11. Cross section SEM image of (a) 100 micrometer Si wafer and (b) 300 micrometer Si wafer

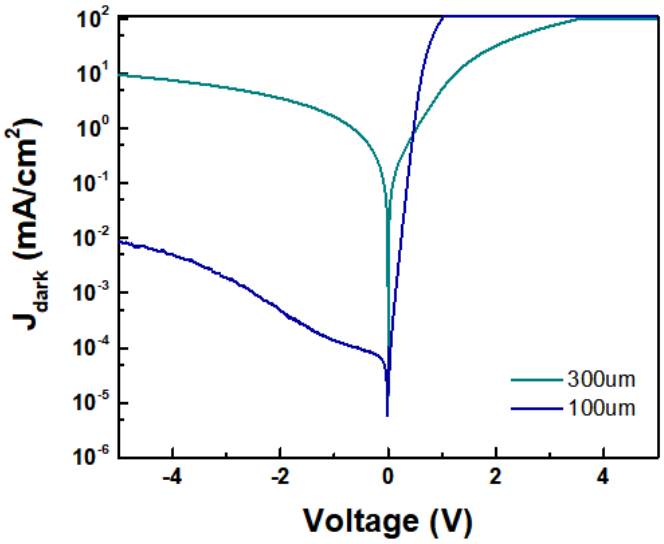



Fig.12. Dark I-V curve of etched Si solar cell

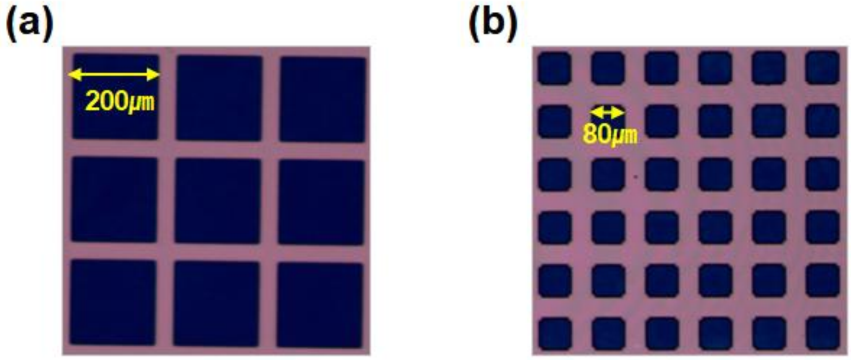



Fig.13. Etching pattern condition (a) large hole condition (b) small hole condition

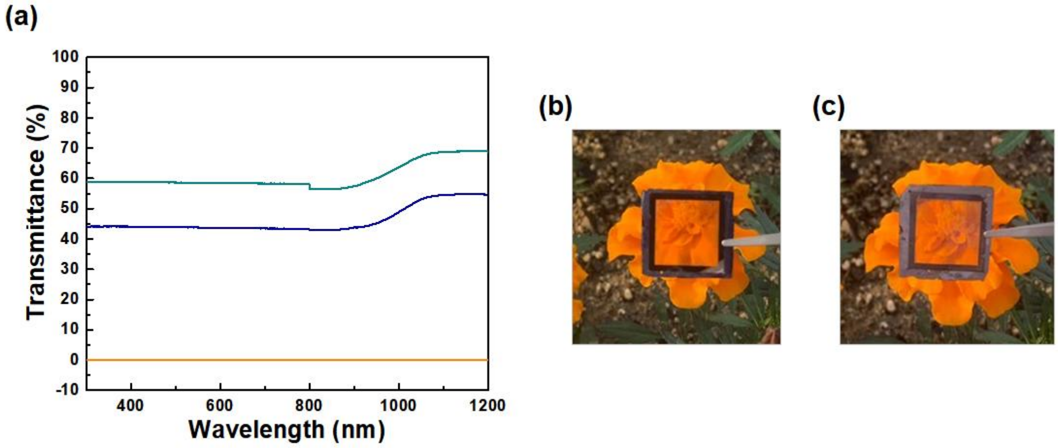
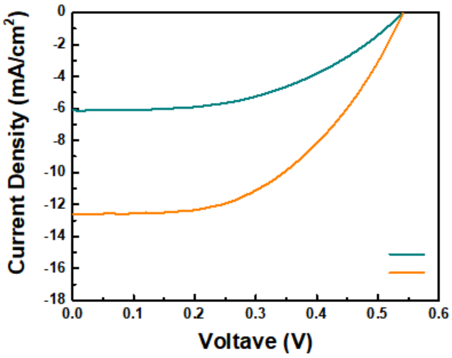



Fig.14. (a) Transmittance of etched Si. Green line is a large hole condition (b), and blue line is a small hole condition (c), yellow line shows bare Si reflectance.




| Pattern | Jsc(mA/cm$^2$) | Voc(mV) | FF(%) | PCE(%) |
|---|---|---|---|---|
| Large Hole | 6.0 | 535 | 51.3 | 1.65 |
| Small Hole | 12.6 | 538 | 51.2 | 3.47 |

Fig.15. J-V curve of transparent Si solar cell.

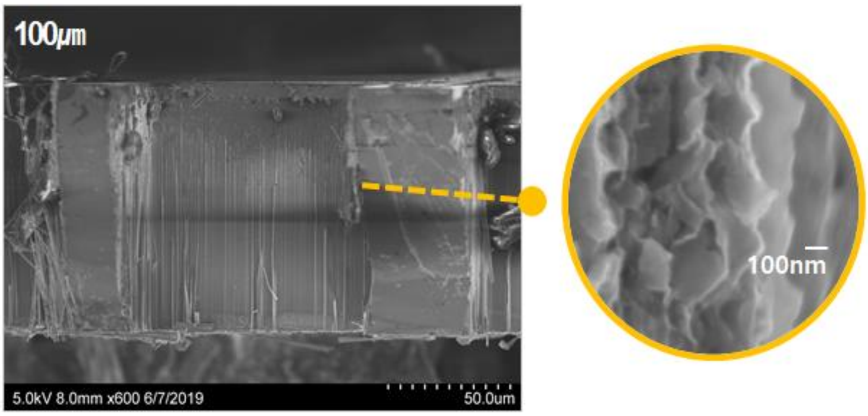



Fig.16. Cross section SEM image of 100 micrometer etched Si

## 4.3 Transparent silicon solar cell optimization

I have used different silicon etching conditions to see if the previous silicon etching conditions have caused much damage to the silicon, causing a reduction in efficiency. This time, in order to increase the amount of passivation of the silicon during the etching, in this experiment, $C_4F_8$ gas was deposited in an amount of 200 sccm for 1s, and $SF_6$ gas was etched in an amount of 300 sccm for 4s. I named this condition "$C_4F_8$ rich condition" and named the former etching condition "$SF_6$ rich condition". Figure 17 shows an etched cross-sectional photograph of $C_4F_8$ rich condition and $SF_6$ rich condition. As can be seen in the figure, $C_4F_8$ rich condition and $SF_6$ rich condition showed similar etch times to similar etch profiles, but when we look closely at the etched sidewall, you can confirm that $C_4F_8$ rich condition is relatively flat compared to $SF_6$ rich condition. This means that since the amount of $C_4F_8$ gas is larger, the silicon is etched with a passivation, so that the damage to the silicon wafer itself is small, which means that etching can be performed without deteriorating the performance. Figure 18 shows the J-V curve of a transparent silicon solar cell fabricated with two etching conditions. It can be confirmed that the FF of the solar cell fabricated by etching with the $C_4F_8$ condition rather than the $SF_6$ rich condition is clearly improved. The large hole condition has a very high transparency suitable for BIPV for windows, but have a low value in $J_{sc}$ because the area of silicon in the remaining active area is small. The small hole condition showed a little lower transparency than the large hole condition but could be applied to the windows BIPV system and the relatively large silicon area remained, showing a high value in $J_{sc}$.

Previously, conventional transparent solar cells showed a specific color due to selective light transmission of organic materials, which could be a big obstacle to window BIPV application. Figure 19 (a) shows the color coordinates of the silicon transparent solar cell used in this experiment. As can be seen in the figure, the transparent silicon used in this experiment was measured to have a neutral color chromaticity coordinate. This means that transparent silicon solar cells are not particularly colored and therefore suitable for window BIPV. In addition, since the thickness of the solar cell is thin in Figure 19 (b), the transparent silicon solar cell produced has some flexibility. Therefore, it is conceivable that a transparent silicon solar cell made by such a process is a solar cell that is very likely to be applied to window BIPV in the future.

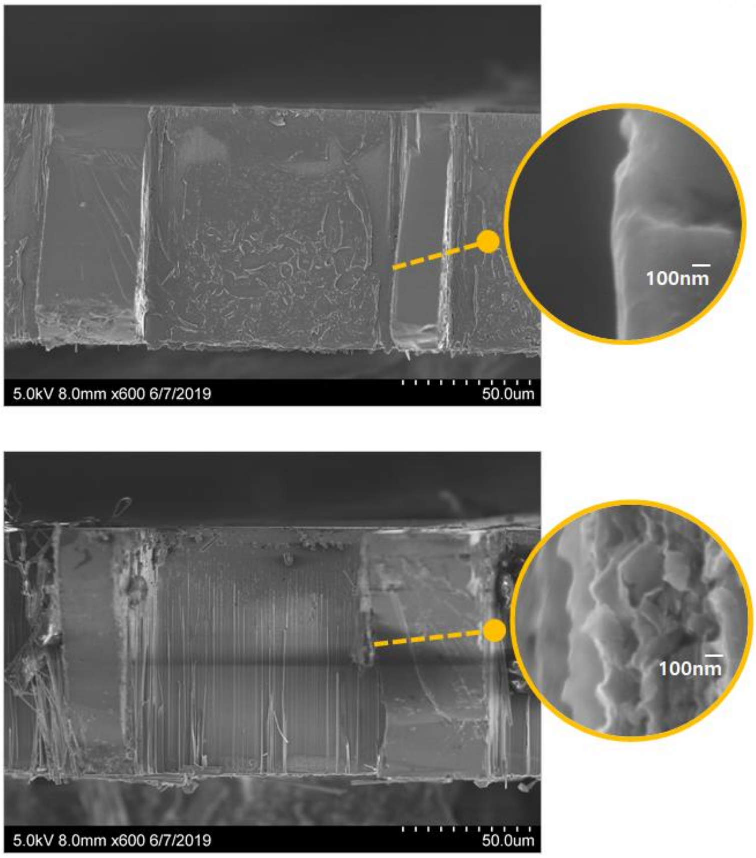
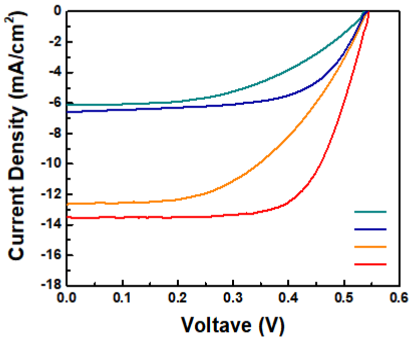



Fig.17. Cross section SEM image of $C_4F_8$ rich condition (top) and $SF_6$ rich condition (bottom)




| Pattern / Etching Condition | Jsc(mA/cm$^2$) | Voc(mV) | FF(%) | PCE(%) |
|---|---|---|---|---|
| Large Hole, $SF_6$ rich | 6.0 | 535 | 51.3 | 1.65 |
| Large Hole, $C_4F_8$ rich | 6.5 | 542 | 62.3 | 2.19 |
| Small Hole, $SF_6$ rich | 12.6 | 538 | 51.2 | 3.47 |
| Small Hole, $C_4F_8$ rich | 13.5 | 545 | 67.4 | 4.96 |

Fig.18. J-V curve of transparent Si solar cell

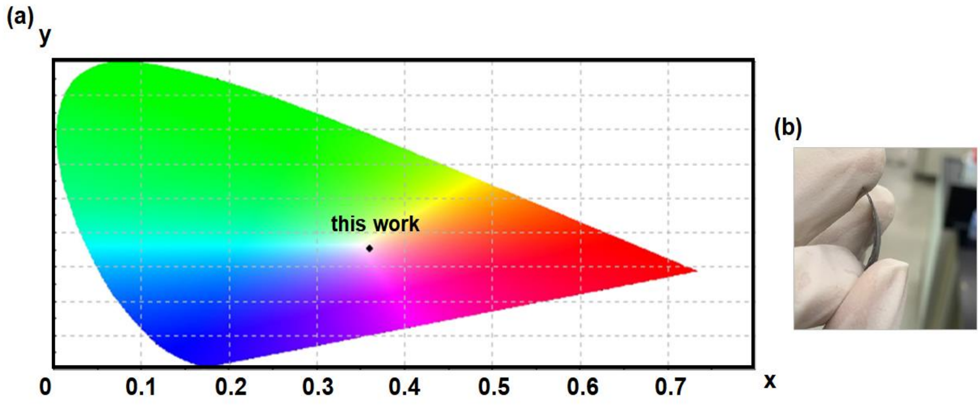



Fig.19. (a) Color coordinates of transparent Si solar cell and (b) small flexibility of fabricated transparent Si solar cell

## 4.4 To get higher efficiency of transparent silicon solar cell

By replacing the former organic transparent solar cells with silicon, I made a transparent silicon solar cell that produces high power. This is shown in Figure S6. Looking at other silicon solar cell processes studied so far, there are ways to get more efficiency. First, if I introduce Back Surfafe Field (BSF) in silicon solar cell, it can increase the value of $V_{oc}$ and FF more than now. Figure S7 shows previous experimental results showing the increase of $V_{oc}$ and FF as a result of introducing $N^+$ BSF into an n-type silicon solar cell. BSF helps to improve the $V_{oc}$ and FF by providing a higher concentration of electric field on the back surface of the silicon wafer, thereby preventing the rear recombination of electrons. In addition, The reflectivity of the silicon surface is lowered to absorb more sunlight, which can contribute to improvement of $J_{sc}$. Figure S8 shows the refelctance spectra of bare Si and black Si(surface texturing wafer). Eventually, transparent silicon solar cells are expected to show efficiencies of more than 7% when performing additional optimization processes such as post etching treatment or additional electrode optimization.

# V. Conclusion

The BIPV system is expected to be of great help in solving existing energy resource problems and is a valuable technology. However, conventional transparent solar cells have problems such as a small active area, unique color, low transparency, and low stability for application to BIPV systems. In this experiment, to solve these problems, I made a transparent silicon solar cell by drilling a fine holes in a silicon solar cell. Transparent silicon solar cells have sufficient transmittance and active area for application in BIPV systems, which is a good fit for commercialization. If more research is done in the future and the efficiency is improved, it is expected to be of great value as a better solar cell for BIPV window.

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# VI. Supplementary data

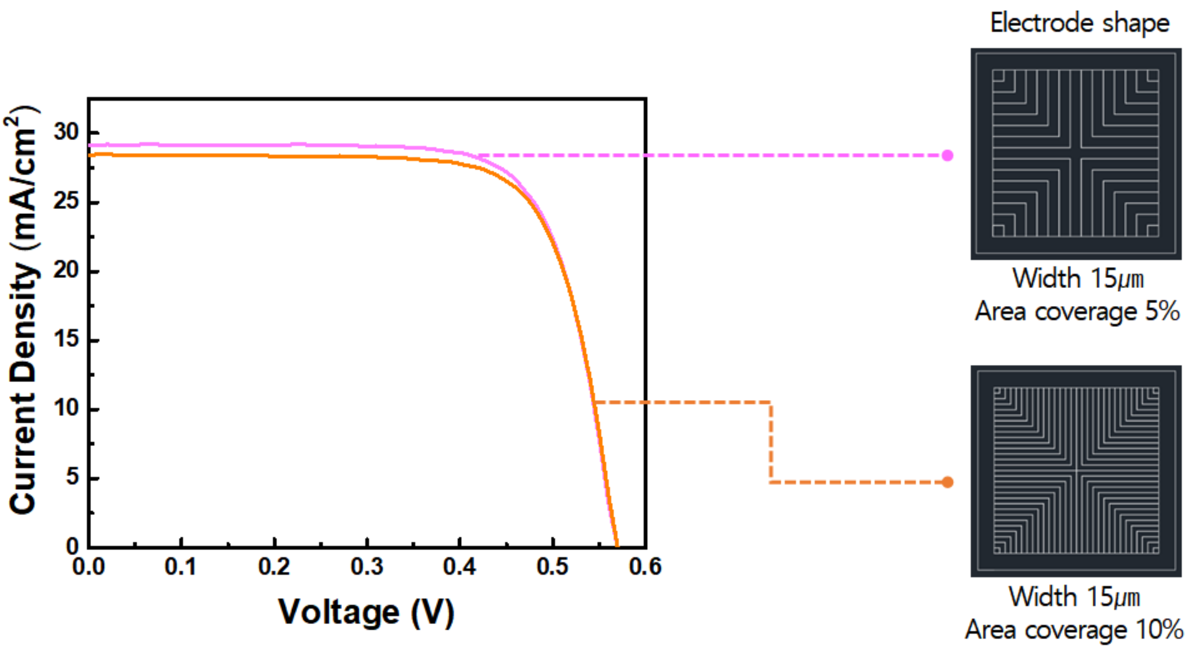
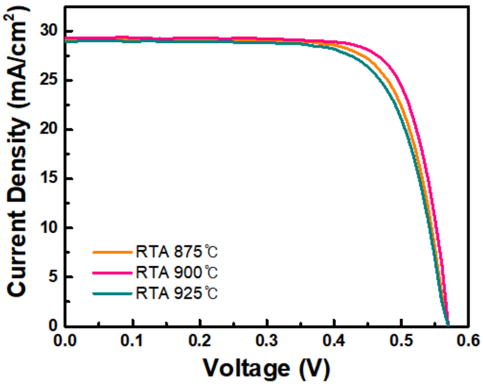



Fig.S1. Optimization of thin Si solar cell by front electrode shape




| | Sheet Resistance | Jsc(mA/cm²) | Voc(mV) | FF(%) | Effi.(%) |
|---|---|---|---|---|---|
| RTA 875℃ | 143Ω/□ | 29.1 | 570 | 73.8 | 12.24 |
| RTA 900℃ | 101Ω/□ | 29.3 | 570 | 75.2 | 12.56 |
| RTA 925℃ | 86Ω/□ | 29.0 | 570 | 72 | 11.90 |

Fig.S2. Optimization of thin Si solar cell by emitter doping level

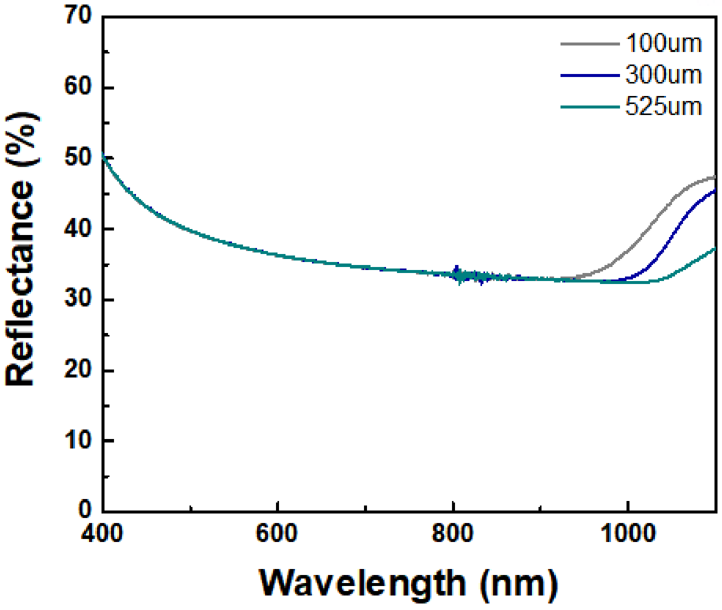



Fig.S3. Reflectance spectra of Si wafer by wafer thickness

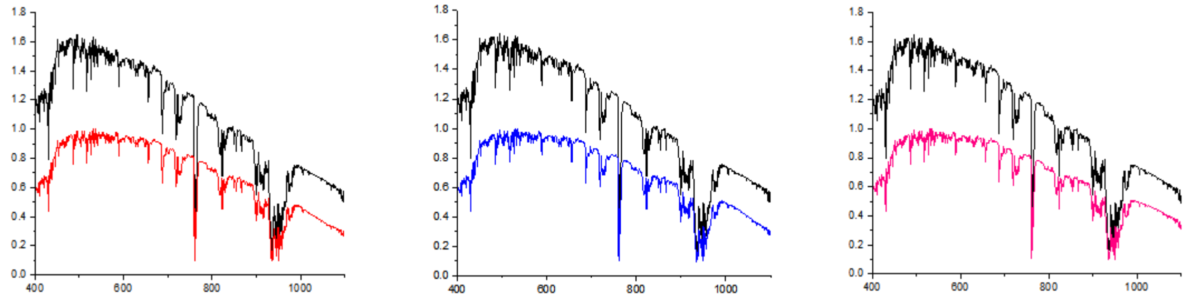



Fig.S4. Absorption spectra of Si by wafer thickness. Black line means AM 1.5G spectra, red line, blue line, pink line means 100um, 300um, 525um Si wafer thickness, respectively

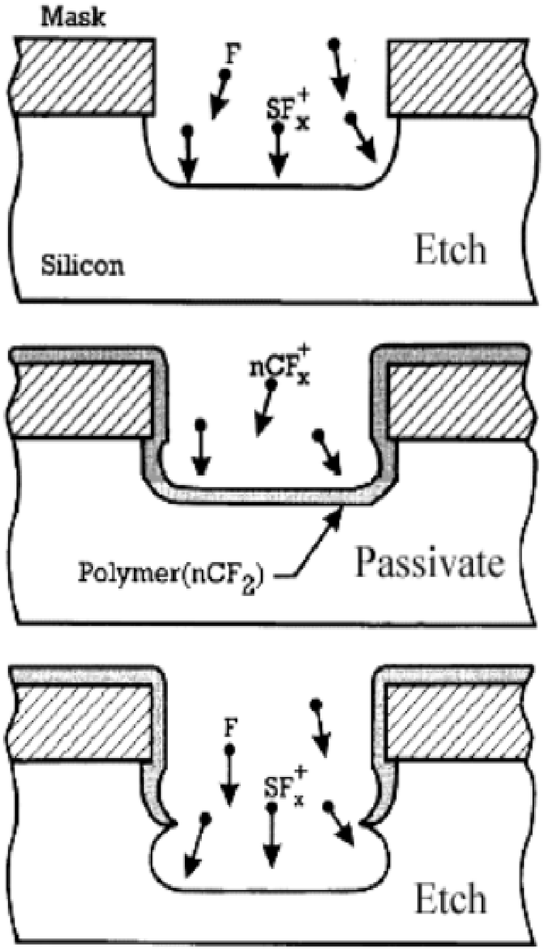



Fig.S5. Schematic figure of bosch process

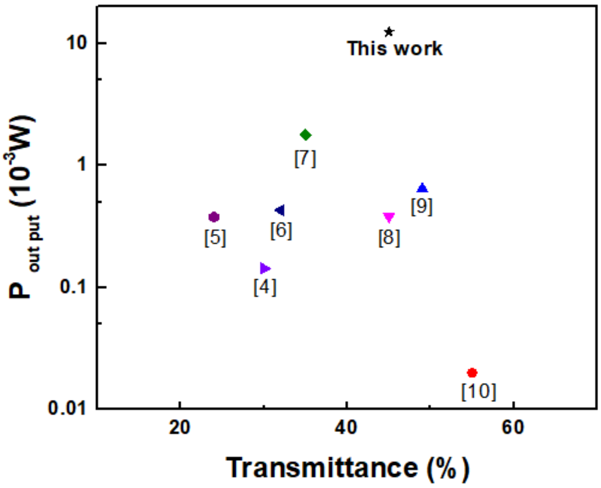



Fig.S6. Power output of various transparent solar cells

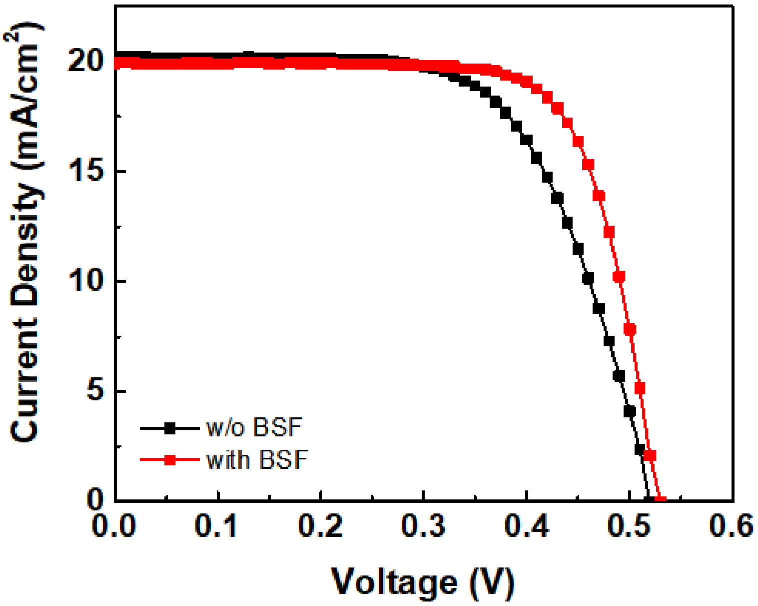



Fig.S7. J-V curve of with/without BSF N-type Si solar cell

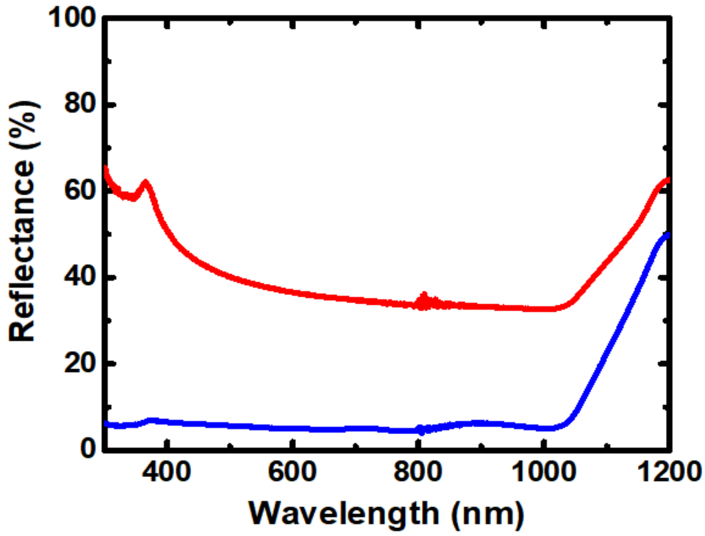



Fig.S8. Reflectance spectra of bare Si (red line) and black Si (blue line)

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