반응성 플라즈마를 이용한 태양전지용 Si기판의 표면 처리

박병욱, 곽동주, 성열문
경성대학교 전기전자공학과

Surface treatment of Si wafer for solar cell using reactive plasma method

Byung-Wook Park, Dong-Joo Kwak, Youl-Moon Sung
Deparment of Electrical and Electronic Engineering, Kyungsung University

Abstract - To lower the fabrication cost of silicon solar cells, a surface treatment using a dielectric barrier discharge instead of a wet cleaning technique was examined on electrode surfaces on silicon solar cells. The fill factor obtained through measuring current-voltage characteristics was evaluated, and the treated surface state was characterized by energy-dispersive X-ray. It was found that the dielectric barrier discharge effectively activated the electrode surface and the surface treatment on finger electrodes contributed greatly to improve the fill factor.

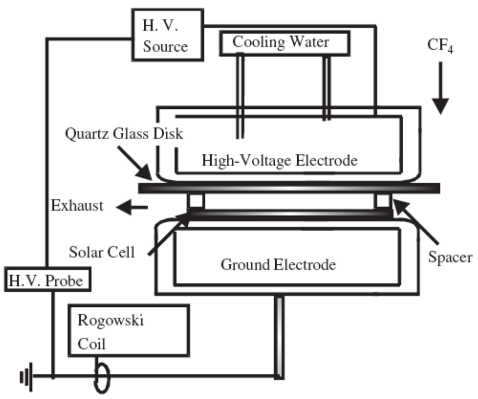
1. Introduction

To popularize the photovoltaic solar system widely, a low-cost photovoltaic solar system with high conversion efficiency should be realized. One approach to realize the requirement is the reduction of the number of process steps. HF wet cleaning in solar cell fabrication is indispensable for the removal of oxide compounds and organic matter from surfaces. However, considering the fabrication cost which contains the disposal cost of waste fluid resulting from wet cleaning processes, it is desired to reduce the number of HF wet cleaning processes. Therefore, we proposed a surface treatment technique using a dielectric barrier discharge (DBD) at an atmospheric pressure[1, 2]. The DBD formation is achieved by the arrangement of dielectric layers in the discharge gap. The dielectric layer leads to the formation of a large number of short-lived micro-discharges whose gas temperature is low even at an atmospheric pressure[1]. Thus, a large number of reactive species are produced in the DBD, allowing us to perform a brief treatment.

This study was focused on whether the plasma-treated electrode surface on the solar cell was activated as well as the electrode surface treated by HF wet cleaning. The electrode surfaces on solar cells were treated using DBD in atmospheric pressure CF4, which replaced the final HF wet cleaning process in the conventional fabrication processes of the solar cell. The fill factor (FF), which reflects the degree of the current transport, was investigated by measuring current-voltage (I-V) characteristics. The DBD-treated electrodes were characterized by energy-dispersive X-ray (EDX) and scanning electron microscopy (SEM).

2. Experiments and results

Figure 1 shows a schematic diagram of the surface treatment system using DBD. A parallel electrode type was used for generating DBD. Each electrode 70 mm in diameter was made of stainless steel and was cooled by passing cooling water at 10℃ through it. The corners of the electrodes were made rounded with a radius of 5 mm to restrain the formation of a concentrated electric field at the edges of the electrodes. As the dielectric material, a quartz glass disk 100 mm in diameter and 1 mm thickness was used. The quartz disk was arranged below a high-voltage electrode, and solar cells for surface treatments were placed on a grounded electrode. The discharge gap length (d) between the quartz glass disk and the front surface of the solar cell was adjusted by placing four kinds of stainless steel spacers (4 mm×25 mm) that differed in thickness, and then d was set to 0.2, 0.4, 0.6 and 0.8 mm. The DBD was operated using a pseudo-sinusoidal wave, of which maximum value and frequency were 4 kV and 8 kHz, respectively. Discharge voltage and discharge current were monitored using a high voltage probe and a Rogowski coil, respectively. The voltage rise time to a maximum value was 5 m, and the full width at half maximum of a voltage pulse was approximately 10 m[2]. The discharge current consisted of the displacement current due to capacitance and current pulses due to short-lived micro-discharges with pulse duration of 5 ns. CF4 (99.99%) controlled by a mass flow controller entered into the chamber from the upper side of the chamber, and its flow rate was maintained at 1.5 l/min. All experiments reported here were performed under atmospheric pressure.

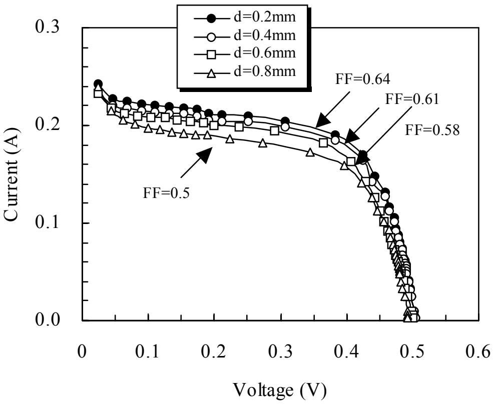


<Fig. 1> Schematic arrangement of experimental apparatus for the surface treatment.

The FF was evaluated by measuring I-V characteristics under the conditions of air-mass 1.5 global (AM 1.5G), 100 mW/cm2, and 25℃. The FF can be described as follows.

$$FF = \frac{V_{op} \times I_{op}}{V_{oc} \times I_{sc}} \quad (1)$$

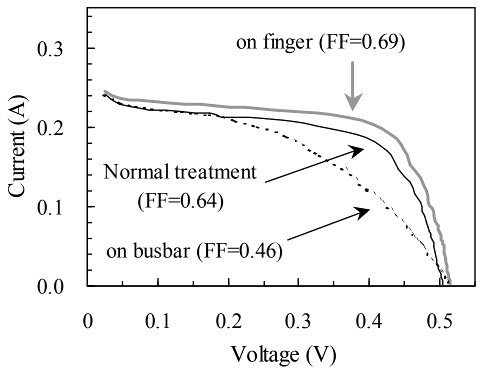
where Voc is the open-circuit voltage, Isc is the short-circuit current, and Vop and Iop are the voltage and current at the maximum power obtained in the I-V curve. I-V characteristics obtained on DBD-treated samples, for the cases of d = 0.2, 0.4, 0.6 and 0.8 mm, are shown in Fig. 2. Vd and the treatment time were kept at 4 kV and 10 min, respectively. Although the breakdown voltage became high with increasing d, the DBD was sustained over the substantial electrode area even at d = 0.8 mm. The discharge powers at d = 0.2 and 0.8 mm, obtained by the integration of the discharge voltage and the discharge current for a pseudo-sinusoidal wave period, were approximately 1.5 and 4 W respectively. At each discharge gap, the discharge powers obtained by 20 measurements accorded within an accuracy of ±8%. As can be seen from Fig. 2, the I-V characteristics were improved by the surface treatments. The calculated values of FF for the cases of d = 0.2, 0.4, 0.6 and 0.8 mm were 0.64, 0.61, 0.58 and 0.50, respectively. These indicate that the cut solar cells were activated by DBD treatments. Additionally, it is found that FF increases with decreasing d. Because electric field becomes high with the decrease of d, the electrode activation is promoted by increasing electric field. It is probable that chemical reactions related to etching were promoted under the high electric field. Then, the further treatments were performed at d = 0.2 mm.



<Fig. 2> I-V curves obtained on the DBD-treated solar cells for the cases of d = 0.2, 0.4, 0.6 and 0.8 mm.

I-V characteristics obtained under various treatment methods are shown in Fig. 3. Each treatment was carried out at d = 0.2 mm, Vd = 4 kV and for 10 min. A solid line shows a profile obtained on a normally treated sample. Here, the entire area corresponding to the substantial electrode area was treated. A dashed line denotes a profile obtained on a sample where only the busbar electrode was treated. In this case, the front surface area, except the surface area of the busbar electrode, was covered by stainless steel tape with a thickness of 0.1 mm. The gap length between the quartz glass and the front surface of the busbar electrode was maintained at 0.2 mm by setting a gap spacer 0.1mm in thickness on the stainless steel tape. A thick line denotes a profile obtained on a sample where only the finger electrodes were treated by covering the front surface area except the surface area of finger electrodes. The calculated values of FF on the normally treated sample, the treated busbar and the treated finger were 0.64, 0.46 and 0.69, respectively. Although the I-V characteristics were improved by the surface treatments, the degree of activation differed among the treatment methods, which will be discussed later. Incidentally, the area of the discharge electrode used in this study was smaller than that of the cut solar cell, in which only 70% of the surface area on the cut solar cell was treated. FF for the normal surface treatment was 0.64; however, a further improvement of FF is expected by increasing the size of the discharge electrode.

EDX spectra obtained on the parent and DBD-treated electrodes were also investigated. Each treatment was carried out at Vd = 4 kV and for 10 min. The parent busbar and finger electrodes were clearly found to contain oxygen (O). The O contents on the parent busbar and finger electrodes were 7.8 and 9.2 at%, respectively. Each value was the average of 5 measurements carried out at arbitrary 5 positions. For the DBD-treated electrodes, the clear spectral peak due to O is not observed. Their O contents were less than 1.5 %. As was the case for the surface treatment using the DBD, the clear spectral peak due to O was not observed on the HF wet-etched busbar and finger electrodes of the cut solar cell whose FF was 0.76. Therefore, it is considered that a dry process using the DBD can yield the same action as the wet etching process. Oxide compounds on electrodes were reduced by the DBD surface treatment, and then the electrode surfaces were activated.



<Fig. 3> I-V curves obtained under various treatment methods at d = 0.2 mm.

Furthermore, it can be seen, from the SEM images obtained on electrodes of the cut solar cell, that there are small holes with a diameter of several m on electrode surfaces. It is noted that a current heat sintering process for electrode formation is liable to produce such small holes and concave finger electrodes. The small hole on the finger electrode centers at the concave part, while that on the busbar electrode uniformly distributes. As mentioned above, the O content on a finger electrode was higher than that on a busbar electrode. This O content was the average of 5 measurements carried out at arbitrary 5 positions around the concave part. O contents obtained at the areas except the concave part were the same as that on a busbar electrode. Therefore, oxide compounds stayed and centered on the hole surfaces on the concave part.

3. Summary

The surface treatments using DBD instead of a wet cleaning technique were performed on electrode surfaces on silicon solar cells. The results showed that DBD could yield the same action as the wet etching process, i.e., oxide compounds on electrodes were reduced by the DBD surface treatment, and then the electrode surfaces were activated. It was also found that the surface treatment on the finger electrode, where oxide compounds stayed and centered on the hole surfaces on the concave part, was considered to play an essential role in the improvement of FF. Thus, we showed that a surface treatment using DBD is a powerful dry process technique for surface cleaning in the fabrication processes of silicon solar cells.

ACKNOWLEDGEMENTS

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[Reference]

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