Effect of N₂ Jet on Si Electrode Surface in Dielectric Barrier Discharge

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Abstract. In order to investigate the effect of discharge gas jet on electrode surface, some dielectric barrier discharge (DBD) experiments were carried out on a laboratory-built DBD system using monocrystalline silicon (Si) electrode in air with or without N₂ jet. The effects of N₂ jet on Si electrode surface are analyzed by means of field emission scanning electron microscope (FESEM) and energy dispersive X-ray spectroscopy (EDS) attached to FESEM. The results show that Si electrode surface roughness and oxidation with N₂ jet are increased more than without N₂ jet. It can be used for texturing solar cells surface to improve power conversion efficiency.

1. Introduction
Atmospheric pressure low temperature plasmas have been investigated widely as a possible replacement for low pressure plasma due to its lower cost and online process. Among the atmospheric pressure plasmas, dielectric barrier discharge (DBD) or silent discharge plasma is easy to generate and stable in open air on ambient conditions. As well known, DBD has been known for more than 100 years [1]. It was mainly applied for ozone production. In the last twenty years, DBD was also used in surface modification, plasma assisted chemical vapor deposition (PECVD), pollution control, excitation of CO₂ lasers and lamps, and plasma display panels [2-6]. DBD is characterized by the presence of at least one insulating (dielectric) layer in the discharge gap between two electrodes. When a high alternating current voltage is applied to DBD configurations, many tiny breakdown channels (generally called microdischarges) are formed in the discharge gap. These microdischarges are characterized as a weakly ionized plasma containing electrons with energies up to 10 eV and ions at room temperature. The plasma also contains UV photons and metastables [7]. DBD is a simple but effective source for generating low-temperature non-equilibrium plasma.

According to discharge modes, DBD includes filamentary, patterned and diffuse discharge [8]. Discharge modes can be changed by altering electrodes, barrier dielectrics, gas and external conditions. The electrode is an important part to affect DBD discharge efficiency. Fang et al [9] investigated the electrode structure on discharge mode and polypropylene surface modification. On the contrary, DBD also have influence on electrode surface. In our previous researches [10], we investigated the effect of air DBD on copper electrode surface and found that surface etching and oxidation occurred on electrode surface. But the effect of discharge gas on electrode surface have not been investigated. Park et al [11] studied multicrystalline silicon surface texturing by plasma etching using a pin-to-plate-type remote dielectric barrier discharge and found it is useful for surface modification. Single crystalline is more
useful for solar cell. To best of our knowledge, the effect of gas jet on single crystalline electrode surface has not been reported. And it is important for silicon solar cell surface texturing. Moreover, it affects electrode lifetime and discharge modes of DBD.

The current interest of this paper is to investigate the effect of N₂ jet on Si electrode surface. The main paper is arranged as follows: (1) the description of experimental setup and measurement methods, (2) the description of electrical characteristics of DBD with N₂ jet and without N₂ jet, (3) the effect of DBD with N₂ jet and without N₂ jet on Si electrode surface topology and surface chemical compositions, and (4) the discussion on the mechanism of the two different DBD on Si electrode surface.

2. Experimental

2.1. Experimental setup

Figure 1 is an experimental setup used in DBD discharge system. The setup includes power supply, discharge chamber and measure apparatus. The power supply can provide high voltage which the frequency can be adjusted in the range from 10 kHz to 40 kHz. The frequency is set to 18.8 kHz. In order to compare the experiments, the direct voltage of power supply is set to 45V due to its easy control. The details of the power supply can be obtained elsewhere [12]. Discharge chamber includes two electrodes, a dielectric barrier and safety cover. The discharge is generated between the two asymmetric parallel plane electrodes. The upper electrode is a 29.5 mm thick aluminum solid cylinder which diameter is 60 mm. The lower one is a circular semiconductor monocrystalline Si wafer with thickness of 0.4 mm and 50 mm in diameter. The dielectric barrier is a quartz glass plate with thickness of 1 mm. The air gap is set to 2.5 mm. The experiment is done in a static system in air with N₂ jet or without that at ambient temperature. In DBD with N₂ jet, the N₂ flowing rate is about 60L/min.

2.2. Measurement

The applied voltage was measured using a high voltage probe (Tektronix P6015A, 20kVDC, 100MΩ, 1000:1). The discharge current and transported charge was measured by a current probe (Tektronix TCPA300) and a 2.2nF capacitor (Cm) placed between the bottom electrode and the ground. The Lissajous figure can be obtained on the oscilloscope screen by plotting the transported charge on the Y-axis and the applied voltage on the X-axis. A Tek TDS220 (100MHz, 1Gs/s) digital oscilloscope was used to record the voltage and current waveform and the Lissajous figure.

In order to analyze the effect of N₂ jet on Si electrode surface, the surface changes of Si electrodes are characterized by field emission scanning electron microscopy (FESEM, SIRION-100, FEI, the Netherlands), and the element contents of the samples were analyzed by EDS (GENESIS-4000, EDAX, USA) attached to the FESEM under electron flux at an acceleration voltage of 25.0 kV. The high resolution of FESEM is 1.5nm at an acceleration voltage of 10.0kV or higher. The resolution of EDS is 130eV and the line width of beam exposure is lower than 100nm.
3. Results and discussion

Figure 2 is the discharge characteristic of DBD discharge in air with N₂ jet or without that. Figure 2(a) and Figure 2(b) are applied voltage, discharge current and Lissajous figure without N₂ jet. Figure 2(c) and Figure 2(d) are those with N₂ jet. As seen from Figure 2, the two discharges are filamentary DBD and not glow (or homogeneous) DBD. In each half cycle of the applied voltage, the discharge current has a number of current pulses which are called microdischarges. The magnitude of microdischarge in positive half cycle is lower than that in negative half cycle due to the asymmetric electrode structure. The discharge current starts at the breakdown voltage of air and ends at the peak value of applied voltage.

The DBD discharge is controlled by the effective electric field generated by the collective action of external electric field and reverse electric field which is produced by charge accumulated at the surface of barrier dielectric. When the effective electric field is lower than the breakdown electrical field of air, the discharge extinguishes. When the complex electric field is higher than the breakdown electric field of air, the discharge occurs again. In the positive half cycle, the charge accumulated at the barrier dielectric surface produced an electric field as the same direction as that of applied voltage. This enhances the electric field in the gas distance and the discharge occurs at a lower applied voltage in positive half cycle. And it also causes that the current pulse in positive half cycle is smaller than that in negative one.

The Lissajous figures are also shown in Figure 2 of DBD. The energy consumed during one cycle of the applied voltage can be calculated from Lissajous figure, which is equal to the enveloped area of Lissajous figure. The discharge power coupled input to the reactor can be calculated by multiplying this area with the frequency of applied voltage. The discharge power calculated by this method is equal to 34.7W for DBD without N₂ jet. As for the DBD with N₂ jet, the discharge power is about 41.1W.
Figure 3 is FESEM images of Si electrode surface treated at different conditions. As shown in Figure 3(a), the control Si wafer surface is relative smooth, homogenous and no specific morphological defects. The FESEM images of DBD in air without N$_2$ jet and that with N$_2$ jet are observed and shown in Figure 3(b) and Figure 3(c), respectively. It can be seen that Si electrode surfaces are etched and their roughness are increased after DBD with different discharge conditions by comparing the three images in Figure 3. Furthermore, the Si electrode surface treated with N$_2$ jet is etched heavier, and its roughness is larger than that without N$_2$ jet. The energetic particles in air plasma bombard the electrode surface and cause surface etching. Moreover, the discharge power is higher and the etching is more serious. As seen from Figure 2, the discharge power with N$_2$ jet is higher than that without N$_2$ jet. So the former electrode surface etching is much heavier than that of the latter.

![Figure 3. FESEM images of Si electrode surface: (a) untreated, (b) treated without N$_2$ jet, (c) treated with N$_2$ jet.](image)
In order to analyze chemical changes of Si electrode surface, EDS attached to FESEM was used for the three samples in Figure 3. And the EDS spectra were shown in Figure 4. The control Si electrode surface only consisted of Si. After air plasma etched, oxygen (O) element was introduced into Si electrode surface. The changes show that oxidation occur into Si wafer surface after DBD air plasma processes. And oxidation is stronger in Si electrode surface with N2 jet DBD than that without N2 jet one.

As well known, there are large numbers of free charged particles including active electrons, ions and neutralized particles in plasma. The high active plasma makes chemical reactions much easier in discharge channels. The temperature of energetic electrons of plasma is up to $10^5$ K ($\approx 10$eV) [13]. A lot of reactive particles can be generated through the collision between electrons and the neutral particles in air. Air plasma includes large numbers of energetic particles and reactive groups, such as N2, N2+, N, N+, N(2D), O2, O2(1Δ), O2+, O2-, O, O(1D), O+, O3, H2O, H2O+, H2, H, OH, and HO2 [14]. Besides these particles, NO is also in air plasma from the emission spectra of DBD [15-17]. When the Si electrode surface is exposed to these particles, surface is oxidized through oxygen-related reactive species such as O, NO, and O3. In this DBD experiment, N2 jet increases the discharge power. Increasing power can improve the contents of oxygenic particles. The added oxygen including species can enhance Si electrode surface oxidation. Thus the contents of O element in Si surface with N2 jet are more than that without N2 jet.

![Figure 4. EDS spectra of Si electrode surface: (a) untreated, (b) treated without N2 jet, (c) treated with N2 jet(color only online)](image)

### 4. Conclusion

It is important to investigate the interactions between air plasma and electrode surface at atmospheric pressure. The present paper studied the effect of N2 jet on surface properties of Si electrode in DBD and compared the experimental results in DBD with N2 jet and without that. After the discharge in air, surface roughness is increased, and surface oxidation is occurred onto Si electrode surface. Surface roughness and oxidation are also enhanced with N2 jet due to the more energetic and oxygen-related species produced in DBD with N2 jet than that without N2 jet.

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References

[1] W. Siemens, Ueberdie elektrostatische Induction und die Verzögerung des Stroms in Flaschendrähten, Poggendorffs Ann. Phys. Chem. 102 (1857) 66.

[2] R. Seeböck, H. Esrom, M. Charbonnier, M. Romand, U. Kogelschatz, Surface modification of polyimide using dielectric barrier discharge treatment, Surf. Coat. Technol. 142-144 (2001) 455.

[3] C.Z. Liu, N.M.D. Brown, B.J. Meenan, Statistical analysis of the effect of dielectric barrier discharge (DBD) operating parameters on the surface processing of poly(methylmethacrylate) film, Surf. Sci. 575 (2005) 273.

[4] C.Q. Wang, X.N. He, Polypropylene surface modification model in atmospheric pressure dielectric barrier discharge, Surf. Coat. Technol. 201 (2006) 3377.

[5] P. Rehn, A. Wolkenhauer, M. Bente, S. Förster, W. Viöl, Wood surface modification in dielectric barrier discharges at atmospheric pressure for creating water repellent characteristics, Surf. Coat. Technol. 174-175 (2003) 515.

[6] U. Kogelschatz, Dielectric-barrier discharges: Their history, discharge physics, and industrial applications, Plasma chem. plasma Process. 23 (2003) 1.

[7] X.P. Lu, M. Laroussi, Optimization of ultraviolet emission and chemical species generation from a pulsed dielectric barrier discharge at atmospheric pressure, J. Appl. Phys. 98 (2005) 023301.

[8] U. Kogelschatz, Filamentary, patterned, and diffuse barrier discharges, IEEE Trans. Plasma Sci. 30 (2002) 1400.

[9] Z. Fang, X. Xie, J. Li, H. Yang, Y. Qiu, E. Kuffel. Comparison of surface modification of polypropylene film by filamentary DBD at atmospheric pressure and homogeneous DBD at medium pressure in air, J. Phys. D: Appl. Phys. 42 (2009) 085204

[10] C.Q. Wang, X.N. He, Effect of atmospheric pressure dielectric barrier discharge air plasma on electrode surface, Appl. Surf. Sci. 253 (2006) 926.

[11] J.B. Park, J.S. Oh, E. Gil, S.J. Kyoung, J.S. Kim, G.Y. Yeom, Plasma texturing of multicrystalline silicon for solar cell using remote-type pin-to-plate dielectric barrier discharge, J. Phys. D: Appl. Phys. 42 (2009) 215201.

[12] C.Q. Wang, X.N. He. Preparation of hydrophobic coating on glass surface by dielectric barrier discharge using a 16 kHz power supply, Appl. Surf. Sci. 252 (2006) 8348.

[13] H.E. Wangner, R. Brandenburg, K.V. Kozlov, The barrier discharge: basic properties and applications to surface treatment, Vacuum 71 (2003) 417.

[14] N.B. Ananth, J.K. Mark, Plasma-polymer interactions in a dielectric barrier discharge, IEEE Trans. Plasma Sci. 33(2005)250.

[15] D. Staack, B. Farouk, A. Gutsol, A. Fridman, Characterization of a dc atmospheric pressure normal glow discharge, Plasma Sources Sci. Technol. 14 (2005) 700.

[16] C.Q. Wang, G.X. Zhang, X.X. Wang, X.N. He, the effect of air plasma on barrier dielectric surface in dielectric barrier discharge, Appl. Surf. Sci. 257 (2010) 1698.

[17] S. Pekárek, J. Rosenkranz, Ozone and nitrogen oxides generation in gas flow enhanced hollow needle to plate discharge in air, Ozone: Science & Engineering, 24 (2002) 221.