

# High-speed etching of amorphous silicon using pin-to-plate dielectric barrier discharge

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## Abstract

Atmospheric pressure plasma was generated using a modified dielectric barrier discharge (pin-to-plate DBD) with the power electrode consisting of multi-pins instead of a conventional blank planar plate. The discharge and amorphous silicon (a:Si) etching characteristics of the pin-to-plate DBD were compared with those of the conventional DBD at various N<sub>2</sub>/NF<sub>3</sub> mixtures. The pin-to-plate DBD showed higher power consumption and higher discharge current than the conventional DBD-type at a given voltage. Therefore, the pin-to-plate DBD appeared to be more efficient than the conventional DBD. In addition, the pin-to-plate DBD showed higher a:Si etch rates than the conventional DBD at various N<sub>2</sub>/NF<sub>3</sub> mixtures. With the pin-to-plate DBD, a maximum etch rate of a:Si of 72 nm/s were obtained with an electrode size of 170 mm × 100 mm, a gas mixture of 0.75% NF<sub>3</sub> in N<sub>2</sub> and an AC voltage of 18 kV when the sample was stationary.

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**Keywords:** Atmospheric pressure plasma; Dielectric barrier discharge; a:Si etching

## 1. Introduction

Atmospheric pressure plasmas have attracted considerable attention in flat panel display (FPD) processing in areas such as photoresist ashing and etching, deposition of organic and inorganic materials, etc. [1–5] Currently, the etching and deposition of FPD materials is mainly performed using low pressure plasma. However, the increasing substrate area and the advent of flexible displays as the next generation FPDs are increasing the demand for processing equipments with low cost, no vacuum processing, easier scalability, etc. Atmospheric pressure plasma equipment might be one solution. However, high-density and uniform plasma over a large area is needed when applying atmospheric pressure plasma to etching and deposition. Among the many types of atmospheric pressure plasma, a dielectric barrier discharge (DBD), which has dielectric plates on one or both of parallel electrodes is generally used in FPD processing because it is a glow discharge-type that can provide an uniform plasma over a large substrate area [6].

However, conventional DBD has a high breakdown voltage and low plasma density due to the high recombination rate at the atmospheric pressure. Therefore, it is difficult to apply this type of plasma to various plasma processing processes such as etching and deposition [7–11].

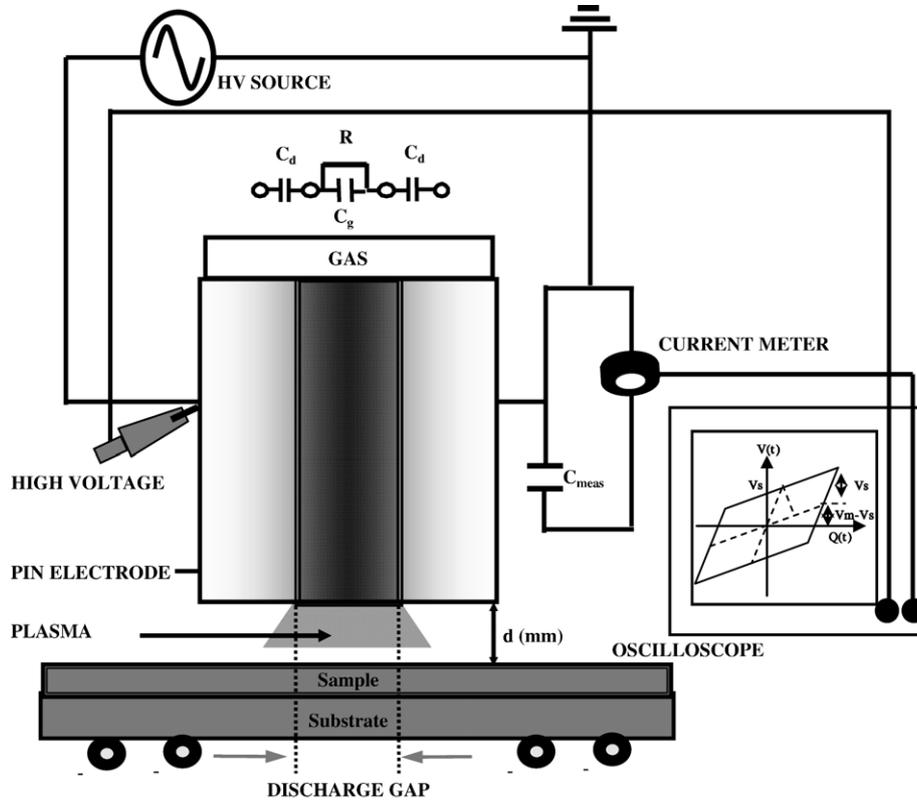
In this study, a pin-to-plate DBD consisting of a multi-pin power electrode instead of a planar power electrode was used to generate high-density plasma at low breakdown voltages [12]. In particular, a remote plasma-type configuration was used in this study in order to prevent damage to the surface of the samples during atmospheric pressure plasma processing. The characteristics of a remote-type pin-to-plate DBD such as the electrical characteristics, plasma characteristics, and a:Si etch characteristics in NF<sub>3</sub>/N<sub>2</sub> gas mixtures were investigated.

## 2. Experimental

Fig. 1 shows a schematic diagram of the system used in these experiments. The discharge source consisted of two parallel electrodes installed vertically above the sample surface, which are a multi-pin powered electrode and a blank ground electrode. These electrodes were covered with a 1 mm thick quartz plate. The discharge gap between the electrodes was 1 mm and the

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**Remote type atmospheric pressure plasma system**

Fig. 1. (a) Schematic diagram of the atmospheric pressure plasma system (pin-to-plate DBD).

distance between the source and the sample was varied from 0.3 to 4 mm. The electrode was 170 mm in length and 100 mm in height. An AC power of 18 kV (rms voltage) (20–30 kHz) was applied to the powered multi-pin electrode to generate atmospheric pressure plasma. As the discharge gas,  $NF_3$  (0–1 slm) was added to 40 slm of  $N_2$  was used to etch a:Si.  $NF_3$  gas was used because it has a higher F atom concentration than other fluorine containing gases such as  $SF_6$ ,  $CF_4$ , etc. [13] a:Si deposited on a  $Si_3N_4$ /glass substrate and patterned using a

photoresist was used as the sample, and the a:Si etch rates were estimated by measuring the etch depth using a step profilometer (Tencor, alpha-step 500) after removing the photoresist. The etch rates were measured as a function of the gas mixture, substrate moving speed, and distance between the source and sample. Scanning electron microscopy (SEM, Hitachi SE-4800) was used to observe the etch profile of a:Si. The voltage and

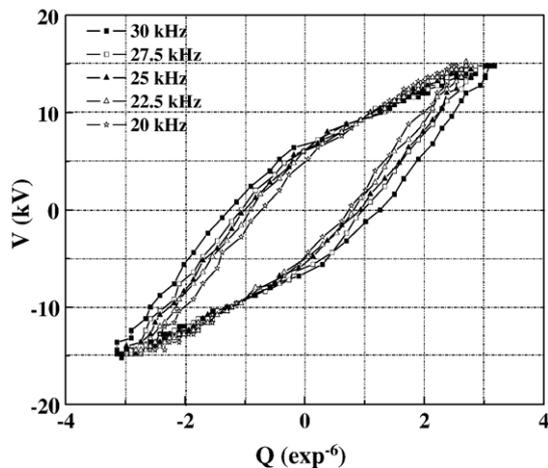


Fig. 2.  $Q-V$  Lissajou curve of the discharge for various frequencies for the pin-to-plate DBD with an electrode size of 170 mm × 100 mm.

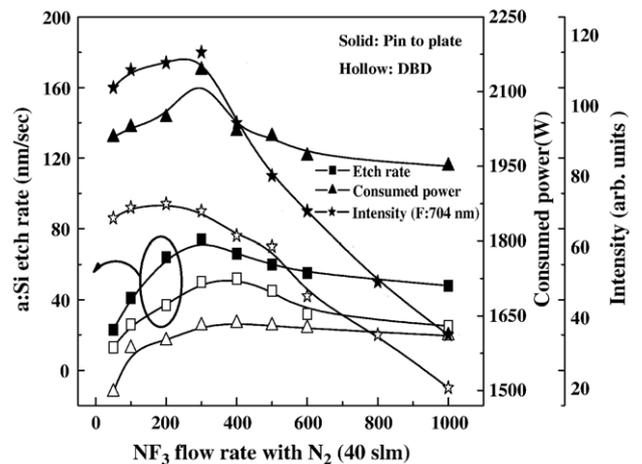


Fig. 3. Effect of  $NF_3$  flow rate in the  $NF_3$ (0–1 slm)/ $N_2$  (40 slm) gas mixture on the a:Si etch rate, power consumption, and relative optical emission intensity of F (704 nm) measured by OES.

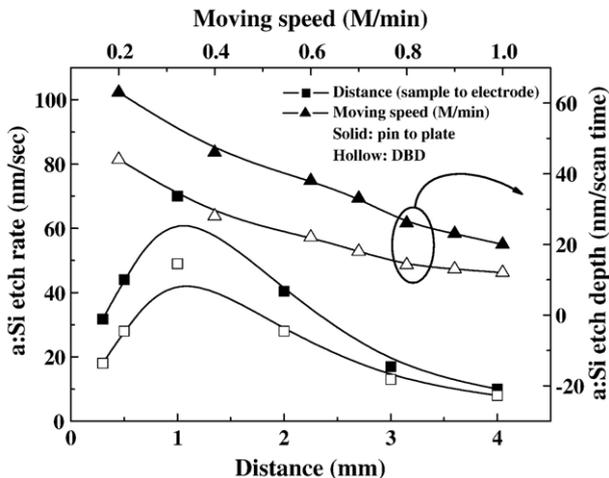


Fig. 4. The a:Si etch rate measured as a function of the distance (sample to electrode) and as a function of the moving speed.

current of the atmospheric pressure plasma was measured using a high voltage probe (Tektronix P6015A) and a current probe (Pearson electronics 6600), respectively. The  $Q$ (charge)– $V$ (voltage) characteristics (Lissajou plot) of the plasma were examined by installing a capacitor ( $C_{\text{meas}}=0.47 \mu\text{F}$ ), as shown in Fig. 1. The species in the plasma was measured using optical emission spectroscopy (OES, SC Tech. PCM-420).

### 3. Results and discussion

Before the etching experiment, the  $Q$ – $V$  plot was investigated as a function of the operating power frequency to determine the optimum operating power frequency. Fig. 2 shows the results for  $\text{NF}_3(300 \text{ sccm})/\text{N}_2(40 \text{ slm})$ , an applied rms voltage of 18 kV, and source to sample distance of 1 mm. From the  $Q$ – $V$  plot (Lissajou curve), the power consumed in the pin-to-plate discharge source was calculated using the following Eq. (1):

$$P = 4fC_d \frac{1}{1 + \beta} V_s(V_m - V_s) \quad (1)$$

Where,  $f$  is the AC power frequency,  $C_d$  is the capacitance of the dielectric material,  $C_g$  is the capacitance of the air gap,  $\beta$  is  $C_g/C_d$ ,  $V_s$  is the dielectric breakdown voltage, and  $V_m$  is the highest applied voltage. The larger area enclosed by the  $Q$ – $V$  plot shows a higher power consumption in the source. The area enclosed by the  $Q$ – $V$  Lissajou curve increased with increasing the operating frequency from 20 to 30 kHz, as shown in the figure. The consumed power calculated by Eq. (1) was increased from 1750 W to 2100 W. Indeed, the discharge current measured by a current meter (Fig. 1) also showed a continuous increase in discharge current with increasing operating frequency. (data not shown) Therefore, the highest power consumption was obtained at 30 kHz. Moreover, the highest a:Si etch rate was also obtained at 30 kHz under the conditions shown in Fig. 2.

While keeping the operating power frequency at 30 kHz, the etch rate of a:Si was measured as a function of the  $\text{NF}_3$  flow rate (50–1000 sccm) in  $\text{N}_2$  (40 slm) for the pin-to-plate DBD whilst

keeping the applied rms voltage at 18 kV and the source to sample distance to 1 mm. As shown in Fig. 3, in addition to the a:Si etch rate, the consumed power was estimated by the  $Q$ – $V$  curve, and the F atomic emission intensity emitted from the source was measured by OES. The characteristics of the pin-to-plate DBD were compared with those of the conventional DBD by measuring the etch rate of a:Si, the consumed power and F atomic emission intensity for the conventional DBD using a blank planar power electrode instead of a multi-pin power electrode. As shown in the figure, the etch rate of a:Si with the pin-to-plate DBD increased with increasing  $\text{NF}_3$  flow rate up to 300 sccm (0.75% in  $\text{N}_2$ ). However, further increases in the  $\text{NF}_3$  flow rate decreased the a:Si etch rate. The variation in the a:Si etch rate with the  $\text{NF}_3$  flow rate also appears to be related to the variation in power consumption in the source at a constant applied rms AC voltage to the power electrode, which alters the F atomic density in the plasma. As shown in the figure, similar to the a:Si etch rate, the power consumption increased from 2 to 2.15 kW with increasing  $\text{NF}_3$  flow rate from 50 to 300 sccm. Further increases in the  $\text{NF}_3$  flow rate resulted in a decrease in power consumption. The variation in the F atomic emission intensity with the  $\text{NF}_3$  flow rate was also similar to that of the a:Si etch rate. Therefore, the highest F atomic intensity was obtained near 300 sccm  $\text{NF}_3$ . The highest power consumption near 300 sccm  $\text{NF}_3$  is believed to be related to the change in the plasma discharge mode with increasing  $\text{NF}_3$  flow rate. When the  $\text{NF}_3$  flow rate is >300 sccm, the observed discharge mode changes from a glow discharge to a filamentary discharge. Hence, a higher power consumption and higher F atomic density occur when the discharge is maintained as a glow discharge. When the consumed power, F atomic emission intensity, and a:Si etch rate for the pin-to-plate DBD were compared with those of the conventional DBD, the pin-to-plate DBD showed approximately 1.3 times higher consumed power at a given AC voltage (18 kV) in addition to a lower ignition voltage and

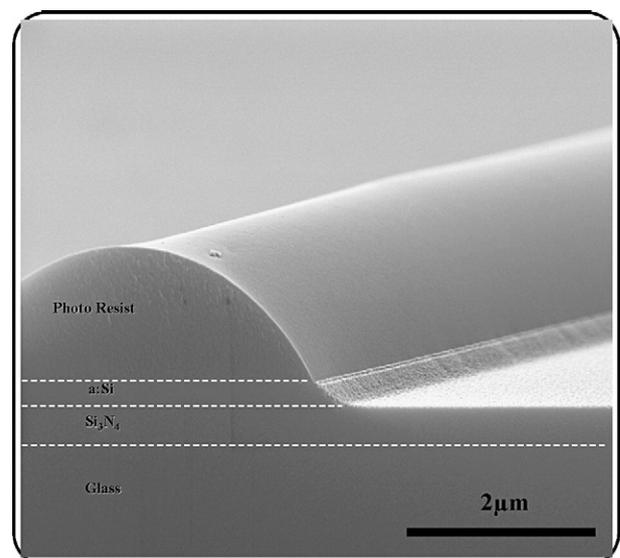


Fig. 5. SEM micrograph of a TFT-LCD substrate (PR/a:Si/Si<sub>3</sub>N<sub>4</sub>/glass) after the etching using the pin-to-plate DBD.

higher discharge current (not shown), a 1.8 fold higher F atomic emission intensity, and 1.5 fold higher a:Si etch rate at the same operating parameters. Therefore, the pin-to-plate DBD is a more efficient discharge source than the conventional DBD with higher plasma density at a given operating voltage. A maximum a:Si etch rate of 72 nm/s, which corresponds to about 4  $\mu\text{m}/\text{min}$ , was obtained using the pin-to-plate DBD at  $\text{NF}_3(300 \text{ sccm})/\text{N}_2(40 \text{ slm})$ , 18 kV of applied rms voltage at 30 kHz, and 1 mm of the distance between the source and sample.

The etch rate of a:Si shown in Fig. 3 was obtained by keeping the sample stationary under the plasma source. In contrast, the substrate needs to be moved at a constant speed under the plasma source for in-line processing when the substrate for a FPD is etched using the remote-type DBD. Fig. 4 shows the effect of the substrate moving speed (0.2–1.0 m/min) on the etch depth/scan (etch depth obtained after a single scanning of the substrate under the remote-type DBD sources) of a:Si for the condition applied AC voltage of 18 kV at 30 kHz,  $\text{NF}_3(300 \text{ sccm})/\text{N}_2(40 \text{ slm})$ , and a 1 mm distance between the source and sample. In addition, the etch rate of a:Si as a function of the distance (0.3–4 mm) between the source and sample were measured at 30 kHz 18 kV rms voltage,  $\text{NF}_3(300 \text{ sccm})/\text{N}_2(40 \text{ slm})$ . The experiment was carried out for both the pin-to-plate DBD and the conventional DBD. As shown in the figure, when the distance between the source and sample was varied, the a:Si etch rate was highest when the source to sample distance was 1 mm for both the pin-to-plate and conventional DBD, even though the pin-to-plate DBD had a higher etch rate than the conventional DBD. When the distance was  $<1$  mm, the etch rate appeared to decrease due to the removal of F atoms without reacting with a:Si on the surface as a result of the higher gas speed on the sample surface. Moreover, when the distance was  $>1$  mm, the etch rate appeared to decrease due to the decrease in the concentration of F atoms through the increased recombination of F with other molecules before reaching the surface. When the substrate moving speed was increased from 0.2 to 1.0 m/min at a source to sample distance of 1 mm, the etch depth/scan the pin-to-plate and conventional DBD decreased almost linearly from 63 nm to 20 nm/scan, and from 43 to 10 nm/scan, respectively. The decrease in etch depth/scan with increasing scan speed is related to the decrease in the exposure time of F atom with the substrate. Generally, the in-line TFT-LCD processing speed is approximately 0.7 m/min currently. At 0.7 m/min, the etch depth/scan of a:Si for the pin-to-plate DBD and conventional DBD was 33 nm/scan and 18 nm/scan, respectively. The thickness of a:Si used for TFT-LCD processing is approximately 200 nm. Therefore, using approximately six scans or by using a six pin-to-plate source in parallel, all the a:Si can be etched away for the pin-to-plate DBD while 11 scans or eleven sources in parallel were needed with the conventional DBD. Therefore, using pin-to-plate DBD, it is believed that the a:Si etch process which is currently carried out using a low pressure plasma etching system can be changed to an atmospheric pressure in-line processing system.

In the case of a:Si etching of a TFT-LCD substrate, a sloped etch profile is needed for the step coverage of the following processes. The etch profile of a:Si (1.5  $\mu\text{m}$  thick PR patterned a:

Si (350 nm) on  $\text{Si}_3\text{N}_4(450 \text{ nm})/\text{glass}$ ) was observed by SEM (Fig. 5) for etching with the pin-to-plate DBD for 5 s without moving the substrate. The etch conditions are as follows:  $\text{NF}_3(300 \text{ sccm})/\text{N}_2(40 \text{ slm})$ , 30 kHz 18 kV of applied rms voltage, and a source to sample distance of 1 mm. As shown in the figure, a:Si was etched completely and a sloped etch profile similar to the isotropic etch profile could be observed.

#### 4. Summary

A modified DBD discharge, which has a multi-pin electrode instead of a blank plate electrode, was used to obtain a higher plasma density than with a conventional DBD discharge, and its discharge characteristics and a:Si etch rates were compared with those using the conventional DBD. The pin-to-plate DBD showed a lower breakdown voltage, higher discharge current, and higher power consumption at a given AC voltage with various  $\text{N}_2/\text{NF}_3$  mixtures than the conventional DBD. Therefore, the pin-to-plate DBD appears to be more efficient and have a higher plasma density than the conventional DBD. In addition, at a given voltage, the a:Si etch rate was higher with the pin-to-plate DBD due to the higher dissociation rate of  $\text{NF}_3$  molecules. A maximum a:Si etch rate of 72 nm/s could be obtained when the substrate was stationary using a gas mixture of 0.75 %  $\text{NF}_3(300 \text{ sccm})$  in  $\text{N}_2(40 \text{ slm})$ , a pin-to-plate DBD at 30 kHz 18 kV of AC voltage, and 1 mm source to sample distance.

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