Basic Study of Fine Particle Transfer Using Electrostatic Force Generated by a Microplasma Actuator Type Electrode

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Abstract—Fine particle control has been applied in many fields such as semiconductor manufacturing, indoor environment, and so on. In this study we investigated the fine particle transfer using microplasma actuator type electrode. Microplasma can be generated at around 1 kV due to the thin dielectric with the thickness of 25 µm. 50 µm SiO₂ particles were used as target particles and their movement was observed when the frequency of the applied voltage was changed from 10 Hz to 10 kHz. It was found that removal rate decreased as the frequency of the applied voltage increased, while transfer rate took the maximum value. Especially, 85% SiO₂ particles were transferred to one direction by applying AC voltage with 1 kV and 500 Hz to the electrode. Removal rate was also evaluated as well as transfer rate. It was found that they had different frequency characteristics.

Keywords—Microplasma, dielectric barrier discharge (DBD), plasma actuator, particle transfer

I. INTRODUCTION

There are some problems on fine particle contamination. In semiconductor industry, contaminating particles are generated during operating equipment and make a short circuit by adhering to the wafers [1]. Since downsizing semiconductors has been progressing with scaling law [2], even submicron particles cause some problems. Therefore, controlling particle contamination is essential for manufacturing semiconductor devices and has been investigated using various technology [3]–[5].

Besides, establishing a photovoltaic power system in desert is promising for generating large capacity power since deserts have large amount of solar radiation and area. Thus, studies on solar cell performance at the condition similar to desert have been conducted [6]. However, there are many problems for implementing the system in desert. One of them is dust particles accumulation on the surface of solar cells. This generates harmful effect to the solar cell performance. Therefore, some researchers have been investigating dust particle removal from the solar cells surface [7]–[11].

In this study, we investigated SiO₂ particle transfer using microplasma actuator type electrode. Plasma actuators have been developed by Roth et al. in 1998 [12] and are expected to be a new flow control thanks to the advantages of simple construction, no moving parts, and a short response time [13]. Therefore, not only basic studies [14]–[18] but also applied researches [19]–[24] including using micron size plasma actuator [25]–[28] have been carried out. Additionally, numerical simulations of plasma actuators have been conducted [29]–[32].

However, the electrode which has the same construction with plasma actuators was used for transporting fine particles by the electrostatic forces. Deposited fine particles were charged by the contact with the electrode and the microplasma generated on the surface. Charged particles were moved not by induced flow but by the Coulomb and dielectrophoretic forces. Some researchers conducted dust particle removal applying three-phase AC voltages with the amplitude of around 1 kV to the electrodes [9], [10], [33]. These studies utilized the electric curtain [34] for dust transfer. By contrast, we applied a single-phase voltage to the electrode in order to transfer fine particles in one direction.

II. EXPERIMENTAL METHODS

A. Microplasma actuator type electrode

Fig. 1 shows the schematic image of microplasma actuator type electrode which was used in the series of experiments. Our device consisted of stripe type electrodes (upper and lower electrodes), a dielectric layer, and an insulated layer. Upper and lower electrodes had 39 lines and were placed to overlap with the width of 100 µm as shown in Fig. 1(b). Both electrodes were made of copper. Polyimide was used as dielectric layer. The lower electrodes were encapsulated in Polyimide to avoid generating microplasma at the bottom side. This microplasma actuator type electrode has a capacitive load owing to the electrode configuration. Upper electrodes were energized at high-voltage (HV) and lower electrodes were grounded. The length of both electrodes was 50 mm and the width of high-voltage and grounded electrodes was 200 µm and 600 µm, respectively. The thickness of the dielectric layer was set to 25 µm which enable to generate the plasma at a discharge voltage about 1 kV. The capacitance of this electrode was about 370 pF.
B. Experimental setup

Fig. 2 shows the experimental setup for observing fine particle movement. The high-voltage AC was obtained using a function generator (Tektronix, AFG3102) and a High-Voltage power amplifier (TREK, 5/80) as shown in Fig. 2. The amplitude of the AC voltage was set to 1 kV and the frequency was varied from 10 Hz to 10 kHz. Applied voltage was measured using a high-voltage probe (Iwatsu, HV-P30) and an oscilloscope (Tektronix, TDS 2014). A resistor was connected between electrode and ground for the measurement of the discharge current. The voltage which was applied to both ends of the resistor was measured using a voltage probe (Tektronix, P2220) and an oscilloscope (Tektronix, TDS 2014) and the current was obtained by Ohm’s law.

SiO$_2$ particles (diameter: 50 µm, density: 2.2 g/cm$^3$, and shape: spherical) were used as target particle. Fig. 3 shows the enlarged image of SiO$_2$ particles taken by a light microscope (Leica, DM IL LED). 150 mg of SiO$_2$ particles were placed on the electrode surface before applying the AC voltage and their movement was observed at each frequency when the AC voltage was applied to the electrodes for 3 min.

III. RESULTS AND DISCUSSION

A. Electrical characteristics

The applied voltage and discharge current were measured with the oscilloscope and voltage probes as shown in Fig. 2. Fig. 4 shows the waveforms of the applied voltage and discharge current when the frequency of the applied voltage was set to 50 Hz, 500 Hz, and 5 kHz. Current value increased proportionally to the frequency of the applied voltage and the waveform of discharge current was mainly formed into sinusoidal wave. The microplasma actuator type electrode had a capacitive component due to its construction. Additionally, current spikes occurred at positive-going and negative-going cycle. Current spikes during both cycles were caused by streamer propagation and glow-like discharge [35], [36]. It was confirmed that the peak value of current spikes during positive-going cycle was larger than that during negative-going cycle at all conditions. This was caused by covering lower electrodes with the insulated layer [37].

The power consumption was calculated by integrating the product of the applied voltage and discharge current. Fig. 5 shows the power consumption at each frequency. The power consumption has a proportional relationship with the frequency. This result was in agreement with data reported by other researchers [38]–[40].

B. Particle transfer

The quantity of 150 mg of SiO$_2$ particles was placed on the electrode before applying the voltage. Fig. 6 shows the particle movement when the AC voltage with the frequency
of (a) 10 Hz, (b) 100 Hz, (c) 1 kHz, and (d) 10 kHz was applied to the electrode. As shown in Fig. 6, it took longer time to transfer SiO$_2$ particles at lower frequency. Especially at 10 Hz, it took around 1.5 min to transfer almost all SiO$_2$ particles to the outside part of the electrode. This occurred due to the fact that the number of ions generated during discharge was less as the frequency decreased. Additionally, SiO$_2$ particles were moved to not only the right side but also to other sides (left side, upside, and downside) part of the electrode. It could be considered to be due to particle re-entrainment [41]. SiO$_2$ particles were charged with the same polarity of the electrode by the contact with the electrode and scattered by the electric repellent force. At 100 Hz, many particles were moved to the right side part of the electrode.

This was caused by the asymmetric electric field generated over the electrode by applying the AC voltage. Moreover, the movement of SiO$_2$ particles was completed by applying the AC voltage for about 15 s. It was observed that most of SiO$_2$ particles at 1 kHz and 10 kHz remained on the surface of the electrode as shown in Fig. 6(c) and (d). It is assumed that the movement of SiO$_2$ particles could not follow the inversion of polarity of the applied voltage since the polarity of the voltage was inverted before the charge amount of SiO$_2$ particles was enough to be transferred.

Transfer and removal rate were evaluated quantitatively. The mass of SiO$_2$ particles which were placed on the surface of the electrode, transferred to the right side part of the electrode and removed from the surface were defined as $M_B$, $M_T$, and $M_R$, respectively. Transfer and removal rate were defined and calculated by the following equations.

$$\text{Transfer rate\%} = \frac{M_T}{M_B} \times 100$$

$$\text{Removal rate\%} = \frac{M_R}{M_B} \times 100$$

Fig. 7 shows the transfer and removal rate at each frequency. It was found that they had different frequency characteristics. Transfer rate increased as the frequency increased up to 500 Hz. The maximum value of transfer rate was 85% at 500 Hz. However, transfer rate decreased sharply such as 21% at 1 kHz and 2% at 10 kHz. On the other hand, removal rate maintained over 95% at less than 1 kHz. At 1 kHz or above, removal rate decreased as well as transfer rate such as 35% at 1 kHz and 3% at 10 kHz. The difference between the frequency characteristics was attributed to particle re-entrainment and microplasma. At low frequency, transfer rate was higher than removal rate since movement of SiO$_2$ particles was mainly affected by particle re-entrainment. By contrast, at high frequency transfer rate were close to removal rate. This was caused by the effect of microplasma since many ions were generated during discharge at high frequency.

IV. CONCLUSION

In this study, the transfer of SiO$_2$ particles with the diameter 50 µm in one direction was investigated by applying a single-phase AC high-voltage to the microplasma actuator type
The following conclusions were obtained from the series of the conducted experiments.

1) The power consumed in the microplasma actuator type electrode which was used in this study was calculated and increased proportionally with the frequency of the applied voltage.

2) Movement of SiO$_2$ particles was observed when the frequency was varied from 10 Hz to 1 kHz. It took shorter time to complete the movement at higher frequency up to around 500 Hz. However, at 500 Hz or above many SiO$_2$ particles remained on the surface of the electrode.

3) Transfer and removal rate were defined and evaluated by Eqs. (1) and (2). Transfer rate increased as the frequency increased up to 500 Hz and reached the maximum value of 85% when the frequency was set to 500 Hz. On the other hand, removal rate maintained at over 95% when the frequency was from 10 Hz to 900 Hz. At 1 kHz or above, transfer and removal rate decreased sharply.

**REFERENCES**


