

# Static Elimination of Charged Objects in Vacuum by Pulsed Glow Plasma

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***Abstract***—Static elimination by pulse plasma has been proposed to mitigate electrostatic hazards in vacuum processes of the electronic device fabrication. A model based on the double probe theory and a POP experiment have revealed specific features of the method such as unbalance in positive and negative neutralizing currents and very short elimination time. The fact to be noted is that plasma works as conductor to earth a charged object onto a chamber wall. The potential of the object becomes 0 V without recharging or overcharging irrespective of the polarity of static charge, which is in sharp contrast with corona ionizers where balance in neutralizing currents is essential for the potential approaching 0 V.

## I. INTRODUCTION

Static elimination is an important process in the electronic device fabrication to mitigate electrostatic hazards (e.g., destruction of the MOS gate insulator, electrostatic attraction of air dusts) that decrease the production rate of semiconductor tips. Therefore, a static eliminator called corona ionizer [1]-[4] based on high-voltage corona discharge in air has been used in the factories worldwide. In particular in the organic device industry, vacuum has been considered to be more preferable than air for the fabrication environment [5] because organic materials and devices are rather fragile and degrade in air by reacting with oxygen and moisture. In spite of the importance, there have been few studies so far on the static elimination in vacuum. In order to eliminate a static charge on an insulator, a free charge of the opposite sign and of the same quantity has to be transported onto the insulator to neutralize it. The corona discharge has successfully been applied to the purpose in the atmospheric gas environment as corona ionizers. However, the corona discharge does not work in a low-pressure gas as well as in vacuum; so another idea has been required. Recently, we are proposing the static elimination by the pulsed glow plasma. In the present paper, its concept, mathematical model and results of a POP experiment are presented.

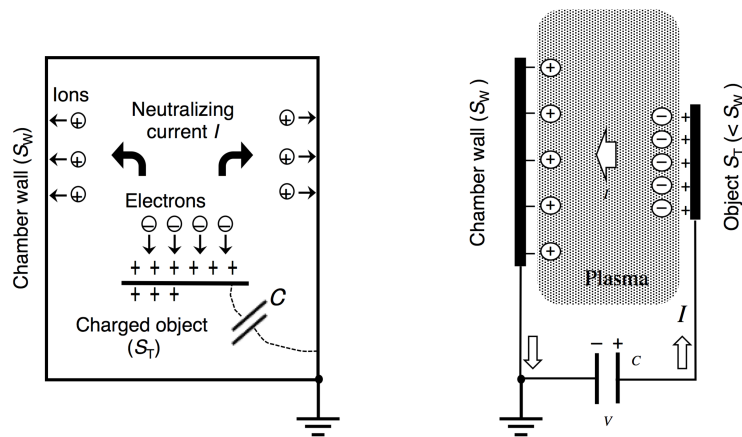


Fig. 1. Model of static elimination in vacuum by plasma. (a) Schematic drawing of the configuration and (b) equivalent circuit of (a).

## II. MODEL FOR STATIC ELIMINATION BY PLASMA

Suppose that a charged object (insulator) with area  $S_T$  is put inside a vacuum chamber with the inner surface area  $S_w$  (electrically earthed) as shown in Fig. 1(a), where  $V_0$  is the initial potential and  $C$  is the stray capacitance of the object. The static charge on the surface is  $Q_0 = CV_0$ . (For example, a sheet with an area of  $1 \text{ m}^2$  set in a vacuum chamber with  $0.1 \text{ m}$  distance makes a stray capacitance of  $180 \text{ pF}$  irrespective of whether it is conducting or insulating.) Plasma is generated in the chamber by some means. We place the following assumptions:

- (i) The plasma has uniform density  $n$  and electron temperature  $T_e$ .
- (ii) The plasma density is maintained constant in time independent of static elimination processes.
- (iii) The ion temperature is zero ( $T_i = 0$ ).
- (iv) The plasma and background gas densities are sufficiently low such that plasma electrons and ions can be regarded as collision-free.

In these circumstances, elimination of the static charge will occur as follows: If the static charge is positive (as shown in Fig. 1(a)), the electric field attracts plasma electrons around the object. The electrons neutralize the positive charge and the potential of the object decreases. The charge neutrality of the plasma breaks a little and the plasma potential  $V_p$  rises. The potential rise then decreases the electron loss and increases the ion loss to the wall. This means that a net electric current flows from the object to the vacuum chamber. In other words, the plasma plays a role of conductor to earth the object. When the charge on the object is negative, plasma ions are attracted. Processes similar to the above but of the reverse polarity happen, but the result is the same; the static charge on the object is eliminated.

The equivalent circuit of Fig. 1(a) is given in Fig. 1(b). This geometry is similar to the asymmetric double probe used for plasma diagnostics [6]. If the area ratio  $S_W / S_T$  satisfies the condition

$$S_W / S_T < J_{es} / J_{is} = 28\sqrt{A}, \quad (1)$$

the current-voltage characteristic is given by

$$I = S_W S_T J_{is} \frac{e^{\frac{eV}{kT_e}} - 1}{S_W + S_T e^{\frac{eV}{kT_e}}}. \quad (2)$$

In (1) and (2),  $J_{is}$  ( $J_{es}$ ) is the ion (electron) saturation current density,  $A$  is the mass number of gas atom,  $I$  is the neutralizing current (circuit current) and  $V$  is the potential of the object at time  $t$ . Equation (2) is plotted in Fig. 2 for  $S_W / S_T = 9$ . From Fig. 2, the following facts are understood:

- (i) The neutralizing current (positive and negative) is independent of  $V$  (constant-current characteristic) except in the range  $V < kT_e / e$ .
- (ii) The neutralizing current is much larger than that of the corona ionizer. Therefore, the static elimination time should be much shorter.
- (iii) The electron current is larger than the ion current by a factor of  $S_W / S_T$ ; it suggests difference in the static elimination time between positive and negative objects.

From (2) and the relation  $I = -CdV / dt$ , the circuit equation is derived as follows:

$$-C \frac{dV}{dt} = S_W S_T J_{is} \frac{e^{\frac{eV}{kT_e}} - 1}{S_W + S_T e^{\frac{eV}{kT_e}}}. \quad (3)$$

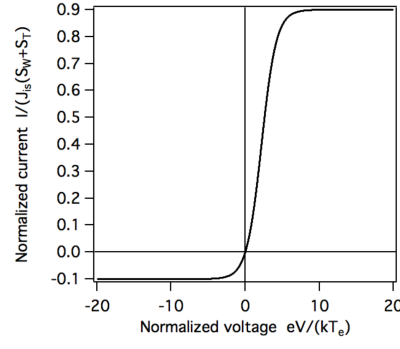


Fig. 2. Normalized current-voltage characteristic of an asymmetric double probe.

Equation (3) can be solved for positively and negatively charged objects separately:

#### A. Positively charged object

The solution of (3) for the initial condition  $V(0) = V_0 > 0$  is given as

$$\hat{t} = \hat{S}_T \left\{ 1 - \hat{V} - \frac{1}{\hat{a}} \ln \left( \frac{1 - e^{-\hat{a}\hat{V}}}{1 - e^{-\hat{a}}} \right) \right\} - \hat{S}_W \left\{ 1 - \hat{V} + \frac{1}{\hat{a}} \ln \left( \frac{e^{\hat{a}\hat{V}} - 1}{e^{\hat{a}} - 1} \right) \right\} \quad (4)$$

where normalized constants and variables are:  $\hat{t} \equiv t/T$ ,  $T \equiv (S_W + S_T)C|V_0|/(S_W S_T J_{is})$  is

the specific time for the static elimination,  $\hat{V} \equiv V(\hat{t})/V_0$ ,  $\hat{a} \equiv e|V_0|/(kT_e)$ ,

$\hat{S}_T = S_T/(S_T + S_W)$ ,  $\hat{S}_W = S_W/(S_T + S_W)$ .

A reasonable assumption  $\hat{a} \gg 1$  simplifies (4) as

$$\hat{t} = \hat{S}_T + \hat{S}_W \hat{V} - \frac{1}{\hat{a}} \ln(e^{\hat{a}\hat{V}} - 1). \quad (5)$$

Furthermore, (5) can be approximated in the range  $\hat{V} \gg 1/\hat{a}$  to

$$\hat{V} = 1 - \frac{\hat{t}}{\hat{S}_T} \quad (6)$$

Equation (6) suggests that the potential decreases linearly with time and the slope is  $1/\hat{S}_T$ .

#### B. Negatively charged object

The solution is given by

$$\hat{t} = \hat{S}_W \left\{ 1 - \hat{V} - \frac{1}{\hat{a}} \ln \left( \frac{1 - e^{-\hat{a}\hat{V}}}{1 - e^{-\hat{a}}} \right) \right\} - \hat{S}_T \left\{ 1 - \hat{V} + \frac{1}{\hat{a}} \ln \left( \frac{e^{\hat{a}\hat{V}} - 1}{e^{\hat{a}} - 1} \right) \right\}. \quad (7)$$

Note that (7) agrees with (4) if  $\hat{S}_T$  and  $\hat{S}_W$  are exchanged to each other. An approximate expression of (7) becomes

$$\hat{t} = \hat{S}_W + \hat{S}_T \hat{V} - \frac{1}{\hat{a}} \ln(e^{\hat{a}\hat{V}} - 1). \quad (8)$$

In the range  $\hat{V} \gg 1/\hat{a}$ , (8) reduces to

$$\hat{V} = 1 - \frac{\hat{t}}{\hat{S}_W} \quad (9)$$

We evaluated expressions (5) and (8) for  $\hat{S}_T = 0.1$ ,  $\hat{S}_W = 0.9$ ,  $\hat{a} = 100$ . Results are shown in Fig. 3. By incidence of plasma electrons and ions, the normalized potential  $\hat{V}$  is found to drop linearly with normalized time  $\hat{t}$  as predicted by (6) and (9). The slope of the positively charged object is larger than that of the negatively charged object by a factor of 9. This result comes from the electron current to ion current ratio of  $I_- / I_+ = J_{is} S_W / J_{is} S_T = 9$ . The speed of the potential drop decreases dramatically in the range  $\hat{V} < 1/\hat{a}$ . This is due to decrease in the neutralizing current in the same range  $V < kT_e / e$  (Fig. 2). In any case, the model predicts that the normalized potential monotonically approaches to zero with time and the static elimination in vacuum by plasma is feasible. It should be noted that in conventional corona ionizers, unbalance (asymmetry) of the neutralizing current gives rise to recharging of the object [1] while it is not true in the static elimination by plasma. This difference may come from the fact that plasma behaves as "conductor" to connect a charged object to the earthed chamber wall. As long as it is true, the final potential of 0V is assured.

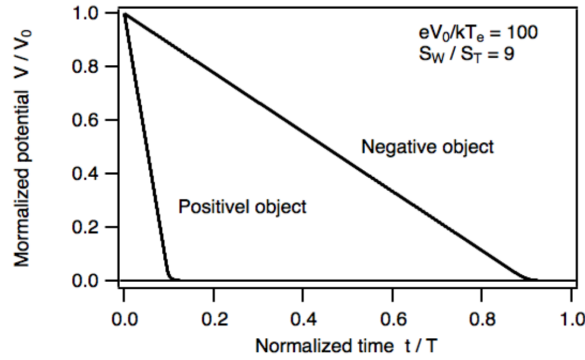


Fig. 3. Evaluation of solutions (5) and (8).

### III. EXPERIMENT

We carried out the proof-of-principle experiment with a setup shown in Fig. 4. A pulsed supersonic valve PSV (R. M. Jordan, C-211) [7] ejects a gas jet of air (ambient air) with duration of about 100 microseconds and maximum repetition rate of 10 Hz. A mesh anode (stainless steel, 81.3% transparency) is installed at 5 mm in front of PSV. To the anode, a positive high voltage of up to 10 kV is applied from a power supply (Trek, 664) through a storage capacitor of 0.2 microfarads and a serial resistor of 100 ohms.

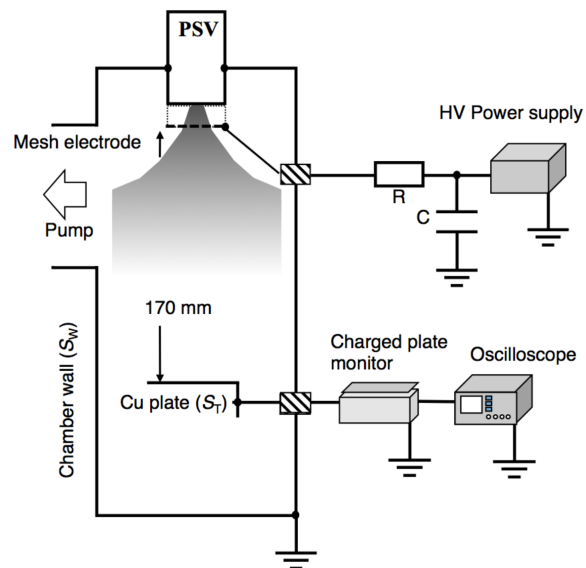


Fig. 4. Schematic drawing of experimental setup.

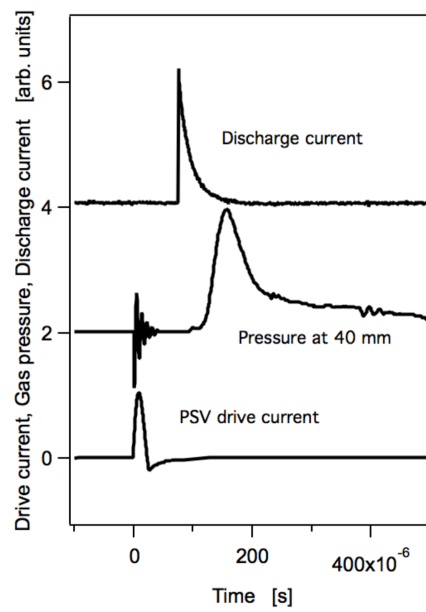


Fig. 5. Typical waveforms of PSV drive current, gas pressure signal (40mm downstream) and discharge current (supply voltage 10 kV).

When the gas jet of sufficiently high pressure fills between the anode and PSV (as a cathode), a pulsed glow discharge happens. The plasma expands through the mesh along with the expansion of the gas jet. At 170 mm downstream from the anode, a copper plate is placed to test static elimination performance. The copper plate is connected to a charged plate monitor CPM (Hugle Electronics, 700A) and is biased between -650 V and +650 V with CPM. The stray capacitance of the plate is estimated to be about 100 pF. Temporal variation in the plate potential during static elimination is measured with CPM and recorded on a digital oscilloscope (Tektronix, TDS2024B).

Figure 5 shows typical waveforms of PSV drive current, gas pressure of the jet and discharge current for a single shot, where the supply voltage was 10 kV and the PSV drive voltage was 1.4 kV. The pressure was measured at 40 mm from the PSV nozzle with a fast ion gage (R. M. Jordan, B-451). The PSV drive current has a form of a half sinusoid with the peak value of about 4000 A. From our previous studies, the gas jet was found to eject at 60 microseconds after the start of the drive current. At 75 microseconds the discharge starts. The waveform gives a peak current of 100 A and a time constant of 20 microseconds as inferred from a CR discharge circuit. The pressure measured at 40 mm starts rising at 100 microseconds and has a half width of around 100 microseconds. (Note that the rise should appear near 60 microseconds, if it was measured at 5 mm (anode position).)

Static elimination of a charged copper plate (20 mm-diameter disc) by plasma was tested for initial biases of +650 V and -650 V. The discharge supply voltage was 5 kV. The Langmuir probe measurement at 170 mm showed the plasma density of about  $10^{16} \text{ m}^{-3}$  and the electron temperature of 15 eV. The result of static elimination is given in Fig. 6. At the moment of discharge, the plate potential in both cases drops abruptly with a time constant of about 15 milliseconds and approaches to a final potential around 0 V. Therefore we can conclude that the feasibility of the static elimination by plasma has been demonstrated.

The observation that the time constant in the potential drop is identical in both positive and negative cases may be incompatible with the model discussed above (see Fig. 3). This is attributed to a limited time-response of CPM. In order to check difference in the static elimination time between positively and negatively charged objects, we connected a capacitor of 10000 pF to the plate. This makes the stray capacitance and therefore the accumulated charge increase by a factor of 100. The result of experiment is shown in Fig. 7. In this experiment, the gas was changed from ambient air to pure  $\text{H}_2$  ( $10^5 \text{ Pa}$ ). The initial bias to the plate (20 mm x 10 mm) was  $\pm 500 \text{ V}$  (corresponding to an accumulated charge of  $\pm 5$  microcoulombs) and the discharge supply voltage was 5 kV. PSV was operated repetitively at 0.25 Hz (once every 4 seconds). In the case of positive bias (Fig. 7(a)), the plate potential drops to zero by a single shot. Thereafter the potential remains around 0V irrespective of successive plasma shots. In the case of negative bias (Fig. 7(b)), on the other hand, the potential drop is 170 V at the first shot and decreases monotonically to 0V with increasing the number of shot. It is obvious that these observations come from asymmetry in the amplitude of electron and ion currents. The incident ionic charge at the first plasma shot is 1.7 microcoulombs. If the duration of plasma is 300 microseconds (inferred from the discharge current waveform), the average ion current is 6 milliamperes; this value is found to be reasonable from plasma parameters.

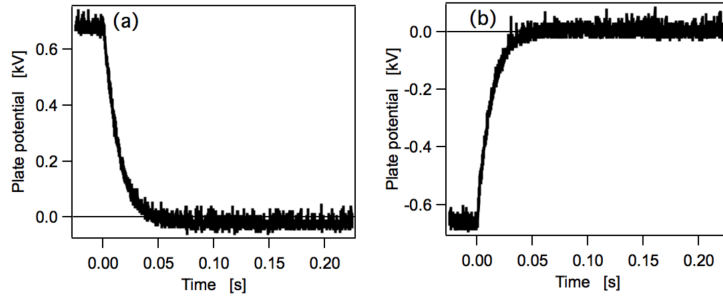


Fig. 6. Static elimination characteristics of (a) positively charged (+650 V) plate and (b) negatively charged (-650 V) plate (stray capacitance of plate  $\sim 100$  pF). Data are obtained at 170 mm downstream from anode.

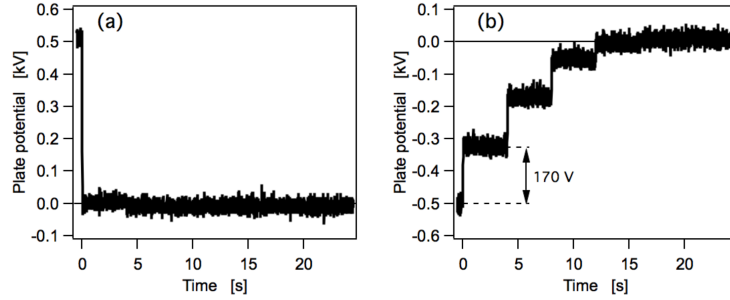


Fig. 7. Static elimination characteristics of (a) positively charged (+500 V) plate and (b) negatively charged (-500 V) plate. Stray capacitance is increased to 10000 pF. Other conditions are similar to those in Fig. 6.

Finally, we discuss on the pressure in the chamber during the static elimination. In our concept, a high-pressure gas is required only in the plasma source (more exactly between the anode and PSV). Because the gas jet expands rapidly in the chamber, we expect that the time and space averaged pressure is kept sufficiently low. The differential equation for the pressure  $p(t)$  in the chamber is expressed [8] as

$$V_c \frac{dp}{dt} = kT\Delta Nf - pS, \quad (10)$$

where  $V_c$  is the volume of chamber,  $T$  is the gas temperature,  $\Delta N$  is the number of molecules ejected from PSV in a single shot,  $f$  is the repetition rate of PSV and  $S$  is the evacuation speed of the pump. The steady-state solution  $p(\infty)$  is obtained by setting  $dp/dt = 0$  as

$$p(\infty) = \frac{kT\Delta Nf}{S}. \quad (11)$$

Note that  $p(\infty)$  is independent of the chamber volume  $V_c$ . Though  $p(\infty)$  can be controlled by the repetition rate  $f$ , the use of large vacuum pump may be very helpful.

Equation (11) is evaluated to be  $p(\infty) = 1.6 \times 10^{-3} f$  [Pa] by using experimental param-



ters:  $\Delta N = 10^{17}$ ,  $kT = 4.0 \times 10^{-21} \text{ J}$ ,  $S = 0.25 \text{ m}^3/\text{s}$ . Observation showed  $2 \times 10^{-2} \text{ Pa}$  at  $f = 10 \text{ Hz}$ . The agreement with calculation is good.

#### ACKNOWLEDGMENT

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#### REFERENCES

- [1] A. Ohsawa, "Precisely balanced ionizer using atmospheric pressure glow discharge in air", *J. Electrostat.* vol. 63, no. 1, pp. 45-57, 2005.
- [2] J. S. Chang and A. A. Berezin, "Neutralisation of static surface charges by a stabilized corona discharge ionizer in a nitrogen environment", *J. Electrostat.* vol. 51/52, no. 1, pp. 64-70, 2001.
- [3] H. Inaba, S. Sakata, T. Yoshida, T. Okada, T. Ohmi, "Neutralization of Wafer Charging in Nitrogen Gas", *IEEE Trans.Semicond. Manuf.*, vol.5, no. 4, pp. 359-367, 1992.
- [4] C. G. Noll, "Balanced static elimination in variable ion mobility environments", *J. Electrostat.*, vol. 49, no. 3/4, pp. 169-197, 2000.
- [5] N. Hattori, T. Fukumoto and T. Kato, "Clean Technology: From Atmospheric Condition to Vacuum", *Shinku*, vol. 33, no. 12, pp.895-899, 1990.
- [6] F. F. Chen, "Electric probes" in *Plasma Diagnostic Techniques*, R. H. Huddlestone and S. L. Leonard, Ed. New York: Academic Press, 1965, pp. 177-183.
- [7] Product catalogue, Jordan TOF Products, Inc. Available: <http://www.rmjordan.com/index.html>.
- [8] A. Roth, "Calculation of vacuum system" in *Vacuum Technology*, 3rd ed. Amsterdam: Elsevier, 2012, pp. 123-148.