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New technique deducing plasma potential by a capacitive coupling method in spraying dielectric barrier discharge plasmas

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A new method to measure the plasma potential in an atmospheric dielectric barrier discharge (DBD) plasmas is developed for a new spraying DBD plasma source, which is sustained by electric fields generated by flowing plasmas at the outer region of the electrodes, since conventional electric probe can not be applied due to arcing. The new technique is to measure the spatially averaged plasma potential by using a capacitive coupling method with calculation of collisional sheath thickness.


I. INTRODUCTION

Dielectric barrier discharge (DBD) has been applied in various areas, such as surface modification of polymer films,1 sterilization,2,3 cleaning of printed circuit board, pollution abatement,4 and surface cleaning of organic contamination.5 For the application of these processes at atmospheric pressure, several ideas have been tried to acquire a stable glow discharge such as One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) (Refs. 6 and 7) and others by using a DBD.

The DBD with parallel electrodes can be characterized by its discharge current shape and pattern of plasma generation area. Kanazawa has demonstrated stable glow plasma at atmospheric pressure by using 13.56 MHz rf and 3 kHz power source, for the first time.8 Gherardi and Massines have shown transition mechanism of discharge mode—filamentary, streamer coupling and glow discharge mode—which is controlled by surface condition and gas flow.9 Golubovskii has demonstrated generation of Townsend and glow homogeneous barrier discharge by numerical simulation.10 He investigated interaction of charged particles with a dielectric surface and showed the results corresponding to experimental data by introducing a finite lifetime of absorbed electrons.11 Kogelschatz classified the dielectric barrier discharge as filamentary, patterned and diffused mode in his review paper.12 Although many researches on glow discharge mode of DBD in parallel electrode geometry have been done, there are few researches on different types of electrode geometry. Pashaie have reported experimental investigation on coaxial dielectric barrier discharge13 and experiments on pin-to-plan discharge have been reported being related with electrical breakdown occurring in industrial devices.14 Since the parallel geometry DBD has small space (a few mm) between the electrodes, there is limitation on the width of processed material. For industrial applications, spraying type DBD plasma is preferred to confined parallel type DBD. Although the cylinder type spraying DBD source15 is already used in industrial area, it also has small cross section of the generated plasma. Besides, the generation mechanism of spraying type DBD plasmas is not well known, yet the use of spraying DBD is growing in industrial areas without sufficient theoretical and/or experimental verification.

In atmospheric pressure plasma, electrons, ions and neutrals suffer various reactions such as ionization, recombination, ion–electron emission, photonemission, desorption, photoionization, relaxation, dissociation, electron attachment, ion-neutral collisions, metastable collision, chemical reaction, etc. However the main reaction for plasma generation is the ionization by electrons. The ionizing energy of an electron comes from the electric field, which is usually confined between electrodes. To generate plasma at the outer region of electrodes for spraying plasma, electrons must escape from the interior region of electrodes with very large energy because the collisional frequencies (νc) of electron and ion with neutrals are orders of 1012 Hz and 109 Hz, respectively. Because the DBD of parallel electrodes cannot extract plasma to spray, to meet the industrial needs of wide spraying DBD sources a new configuration of electrodes should be introduced.

In this article, a new technique measuring plasma potential in spraying DBD plasmas with a simple capacitive probe is introduced for a new spraying DBD plasma generator.16 From the potential measurement of spraying DBD plasma, we have found that the generation of plasma at the outer region of electrodes is sustained by the applied high voltage, which is transferred through conducting plasma.

II. THEORY

If there were no electric field at the outer region of the electrodes in DBD, the velocity of the charged particles will decay exponentially because the charge particle would follow momentum equation of \( m(du/dt) = m\nu_u, \)

\( u = u_0 \exp(-\nu_c) \), and the expected plasma length is order of \( u_0/\nu_c \). Therefore, the electrons should be accelerated by some electric field at the outer region of electrode to sustain plasma flame.

To obtain atmospheric wide spraying type DBD plasma,
many researchers have tried to extract the plasma out of electrode, generated between the electrodes, with strong gas flow. However, our devised DBD plasma system with new electrode configuration showed relatively longer plasma flame compared to conventional system. Because electric field cannot be generated at the outer region of electrodes, long plasma flame length means that there are some electric fields at the outer region of electrodes. To verify the existence of electric field extracting plasma, we measured the plasma potential at the outer region of electrodes. Although electric probes have been widely used for the local measurement of plasma parameters, the conventional electric probe cannot be applied in DBD plasmas because the metal tip of probe will cause electric arc and make the stable plasmas (glow or glowlike) as streamer or arc discharge. To avoid this for measuring plasma potential in a spraying DBD, an indirect method should be introduced.

Figure 1(a) is a schematic of a new capacitive probe to measure plasma potential and Fig. 1(b) shows an equivalent circuit. In Fig. 1(b), if the capacitance of sheath \( C_s \), dielectric \( C_d \) and stray \( C_{st} \) are given, plasma potential can be determined by measuring the voltage applied to the resistance \( R \). Total capacitance of plasma sheath and dielectric barrier is given as Eq. (1) in slab geometry,

\[
C_t = \frac{\varepsilon_d \varepsilon_0 A}{\varepsilon_d s + \varepsilon_0 d} \left[ \text{F/m} \right],
\]

where \( s \) is the sheath thickness and \( d \) is the dielectric barrier thickness, \( \varepsilon_d \) and \( \varepsilon_0 \) are the dielectric constants of dielectric barrier and vacuum, respectively.

Figure 2 shows the variation of total capacitance with sheath thickness. If the sheath thickness is 0.1 mm, then the total capacitance would be decreased by 31%. Therefore, the capacitance of sheath should not be ignored. However, calculation of the sheath thickness at atmospheric pressure has not been established well, and so plasma parameters, which are needed to calculate the sheath thickness, would not be easily obtained for atmospheric plasmas. Nonetheless, for the helium plasma at atmospheric pressure, some main parameters can be calculated by a discharge model for collisional sheath with plane geometry.\(^\text{17}\) The electron temperature in atmospheric helium plasma with slab geometry as is depicted in Fig. 3. Because we have used slab distance of 2 mm in our experiments, electron temperature is calculated as 4 eV from Ref. 17 and it can be used to evaluate the sheath thickness. Other parameter to determine the sheath thickness is the plasma density. The plasma density can be deduced from the above mentioned discharge model\(^\text{17}\) as

\[
T(eV) = \frac{4kT}{2m_e} = \frac{4 \times 1.38 \times 10^{-23} \times 4}{2 \times 9.11 \times 10^{-31}} = 3.2 \text{eV}
\]
\[ n_0 = \frac{P}{e u_B A E}, \]  

(2)

where \( P \) is absorbed power, \( u_B \) is the Bohm velocity, \( u_B = \sqrt{e T_e/M} \), \( A \) is effective area, and \( E \) is total energy loss per ion. The absorbed power of plasma can be calculated from discharge voltage and discharge current. Figure 4 shows the typical discharge voltage and current wave form of the slit type DBD spray. From the wave form graph, the absorbed power and the plasma density are evaluated as 25 W and \( 2 \times 10^{12} \text{ cm}^{-3} \), respectively.

With calculated electron temperature and plasma density as 4 eV and \( 2 \times 10^{12} \text{ cm}^{-3} \), collisional sheath model without ionization is applicable for calculation of sheath thickness.

Momentum collision, Debye length, and ionization mean free path are given as \( l_i = 0.07 \text{ mm} \), \( l_D = 0.01 \text{ mm} \), and \( l_{iz} \), respectively.

The sheath thickness is given with assumption of constant mean free path as Eq. (3) and is given as Eq. (4) with assumption of constant collision frequency model, respectively,

\[ s = \left( \frac{5}{3} \right)^{3/5} \left( \frac{e_0}{3} \right)^{3/5} \left( \frac{2 e_0}{3} \right)^{2/5} \left( \frac{2 e \lambda_i \pi M}{en \mu_s} \right)^{1/5}, \]  

(3)

\[ s = \left( \frac{9}{8} e_0 \mu_s \frac{V_0^2}{en \mu_s} \right)^{1/3}. \]  

(4)

To get the sheath thickness, the ion velocity at the sheath edge \( (u_s) \) must be given. Ion velocity at the sheath edge will be given according to the collisional Bohm condition,

\[ u_s = u_B \left( 1 + \frac{\pi \lambda_i \nu}{2 \lambda_i} \right)^{-1/2}. \]  

(5)

According to Franklin and Snell, \( \lambda_i \) ions cannot reach the Bohm velocity due to collision and collisionless sheath is not formed in front of floating wall in high collisional case. From their calculation, the ion velocity, which is normalized by ion sound speed, at the wall is given as 0.1, whereas Godyak and Sternberg model gives 0.05. In addition to the ion velocity at the sheath edge, voltage difference of plasma and wall \( (V_0) \) should be given to find the sheath thickness. Because dielectric barrier is nonconductor, \( V_0 \) comes from the floating condition as the following: In collisionless plasma, ions get energy from the difference of plasma and sheath potentials to be accelerated to the Bohm velocity. However, collisions in presheath will modify the energy conservation relation as

\[ \frac{1}{2} M u_i^2 + E_c = e (V_p - V_s). \]  

(6)

where \( V_p \) is plasma potential, \( V_s \) is sheath potential, and \( E_c \) is ion energy loss due to collisions. In collisionless and collisional plasmas, electrons are assumed to be governed by the Boltzmann relation. From the floating condition \( (\Gamma_e = \Gamma_i) \), one can obtain the following relation:

\[ V_p - V_f = \frac{1}{e} \left( \frac{1}{2} M u_i^2 + E_c \right) - \frac{T_e}{e} \ln \left( \frac{4 M u_i^2}{e v_e} \right), \]  

(7)

where, \( E_c = \int m_n \nu v dx \) and \( v_e = \sqrt{8 e T_e / \pi m_e} \).

Because the ion collision cross section decreases linearly with ion energy in low energy region, the constant collision frequency model [Eq. (4)] and Eq. (7) are adopted to calculate sheath thickness. For convenience, the term \( \frac{1}{2} M u_i^2 + E_c \) in Eq. (6) is assumed as \( \frac{1}{2} M u_B^2 \). This assumption can be justified.
by the fact that ions would be accelerated to the Bohm velocity \((u_0)\) if there were no collisions.

To get the sheath thickness in collisional plasmas, the plasma density and ion speed at the sheath edge must be given. The plasma density at sheath edge is given as the following:

\[
\frac{n_s}{n_0} = \left(1 + \left(\frac{u_s}{\pi D_a}\right)^2\right)^{-1/2},
\]

where \(D_a\) is the ambipolar diffusion coefficient. From Eqs. (2) to (8), sheath thickness are given as the following:

\[
s = \left(\frac{9}{8} e \mu_0 \left(1 - \frac{1}{2} Mu_s^2 + E_c \right) \frac{T_e}{e} \ln \left(\frac{4u_s}{u_x}\right) \right)^{1/2} + \frac{1}{e} \mu_0 \left(1 + \left(\frac{u_s}{\pi D_a}\right)^2\right)^{-1/2}.
\]

From Eq. (9), collisional sheath thickness is evaluated as 0.02 mm for typical discharge condition as shown in Fig. 4. By using the sheath capacitance, the plasma potential has been deduced as

\[
V_R(t) = V_0 \sin \omega t = V_R f(s),
\]

where \(V_R\) is measured voltage and \(f(s)\) is a conversion factor, which is a function of sheath and will be given later.

### III. EXPERIMENTAL RESULTS

In the equivalent circuit of Fig. 1, the measured voltage over the resistance will be given as following with the assumption of plasma voltage as \(V_0 \sin \omega t\):

\[
V_R = \frac{V_0 R C_t}{1 + R^2 (C_t + C_d)^2} (w \cos \omega t + R (C_t + C_d) w \sin \omega t),
\]

where \(C_t\) is total capacitance and \(C_d\) is stray capacitance. For a large frequency signal, i.e., \(R (C_t + C_d) w \gg 1\), Eq. (11) can be simplified as the following:

\[
V_R = \frac{V_0}{f(s)} \sin \omega t,
\]

where \(f(s) = (C_t + C_d)/C_t\). From the known voltage source, stray capacitance can be expressed in terms of the dielectric capacitance, \(C_d\), and the stray capacitance, \(C_d\) is measured as 12.3 \(C_d\). For the capacitive probe, of our experiment, plasma voltage conversion factor is given as the following:

\[
f(s) = \left(\frac{\varepsilon_d d}{13.3 \varepsilon_d d + 12.3 \varepsilon_d s}\right)^{-1}.
\]

Because the sheath thickness \(s\) is a function of time, the conversion factor should be given as a function of time, too. However, sheath thickness could be treated as a constant near the maximum and minimum values of applied voltage.

With the experimental conditions shown in Fig. 5, the plasma density and electron temperature are given as 1.7 \(\times\) \(10^{13}\) \(\text{cm}^{-3}\) and 4 eV, respectively. The sheath thickness is estimated as about 0.02 mm and the calibration factor of capacitive probe is given as 13.4.

By using the calibration factor, plasma potential \((V_1, V_2)\) at the outer electrodes region are measured by capacitive probe located below the ground electrode, as shown in Fig. 5(a). Figure 5(b) shows plasma potential at the outer electrode region and the plasma potentials of \(V_1\) and \(V_2\) have comparable values with the applied voltage to the hot electrode. The electric field between the probes was about 500 V/cm. It means that there are enough electric fields to pull out plasma to the outer region of the electrodes in the spraying type DBD plasma sources.

Although one may apply this method to less harsh condition such as high vacuum condition, then sheath would be collisionless and relevant capacitances may change, so that it would be an another work equivalent to this. Instead one can figure out the applicable range of this method by finding the maximum error of deduced electric potential. The intrinsic error of this method is evaluated as the following:

\[
\epsilon = \frac{V_R^* - V_R}{V_R + V_R^*} = \frac{k \varepsilon_d (s^* - s)}{2(k + 1) \varepsilon_d d + k \varepsilon_d (s^* + s)},
\]

where \(s^*\) means real sheath thickness, \(s\) is deduced sheath thickness (=0.02 mm), \(k\) is ratio of stray capacitance to dielectric barrier capacitance (=12.3), and \(d\) is dielectric barrier thickness (= 1 mm).

Because the sheath thickness is a key parameter in determining the calibration factor, the intrinsic error can be evaluated from the sheath thickness error. For the plasma density of \(1 \times 10^{11} \text{–} 1 \times 10^{13} \text{cm}^{-3}\) and electron temperature of 1–10 eV, sheath thickness is in range of 0.06–0.006 mm then potential measurement error is within 8%.

### IV. DISCUSSION

By measuring the plasma potential at the outer electrode, electric filed sustaining the plasma generation is deduced with collisional sheath model, which may be related with the build up of charge on the dielectric surface. Dielectric barrier will prevent potential drop on the dielectric surface of end electrode and conducting plasma will transmit the applied discharging voltage to the edge of plasma flame. Along the laminar flow of helium gas at the outer electrode region, discharge can be sustained by sustaining electric field. However, detailed collisional sheath model and mechanism of field generation are to be developed, especially for the case of low plasma density and high electron temperature in the atmospheric DBD plasma.
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