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Discussion on Barrier Discharge by Applying Circuit Theory

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Summary

The dielectric barrier discharge is the useful one as the plasma processing for the decomposition of TOx gas. This paper describes on the equivalent circuit for dielectric barrier discharge. Because we need to know how condition is the most effective on the plasma processing by employing barrier discharge.

The author employed 3-Voltmeters Method and measured the phase difference between voltage and current, the power consumed by barrier discharge and the reactance of barrier discharge. From these measurements, the author has clarified that the equivalent circuit of barrier discharge is the series connection of the resistance and the capacitance. And the author has also reported the condition of the maximum power consumed in discharge.

Key Word: dielectric barrier discharge, equivalent circuit, decomposition of TOx gas

1. Introduction

NOx dissociation is one of the significant problems in the global environmental issues and various processes have been proposed for removing NO gas from exhaust streams [1]. And, there are many papers which were employed the barrier discharge for removing NO gas as a plasma processing [2]. Author is now researching NOx decomposition with employing the barrier discharge as plasma process for removing NO gas [3], [4], [5].

Author is researching how condition of discharge is the suitable one for NOx dissociation, when we apply the barrier discharge for NOx dissociation in this work. Especially, it is main target to know the equivalent circuit for the barrier discharge and to clarify the maximum electric condition of which electric power is consumed in this discharge.

This paper discusses on the equivalent circuit for barrier discharge by measuring the phase difference and employing 3-Voltmeters Method.

2. Experiments

2-1. Experimental Procedure

The schematic figure of experimental apparatus and circuit are shown in Fig.1.These apparatus

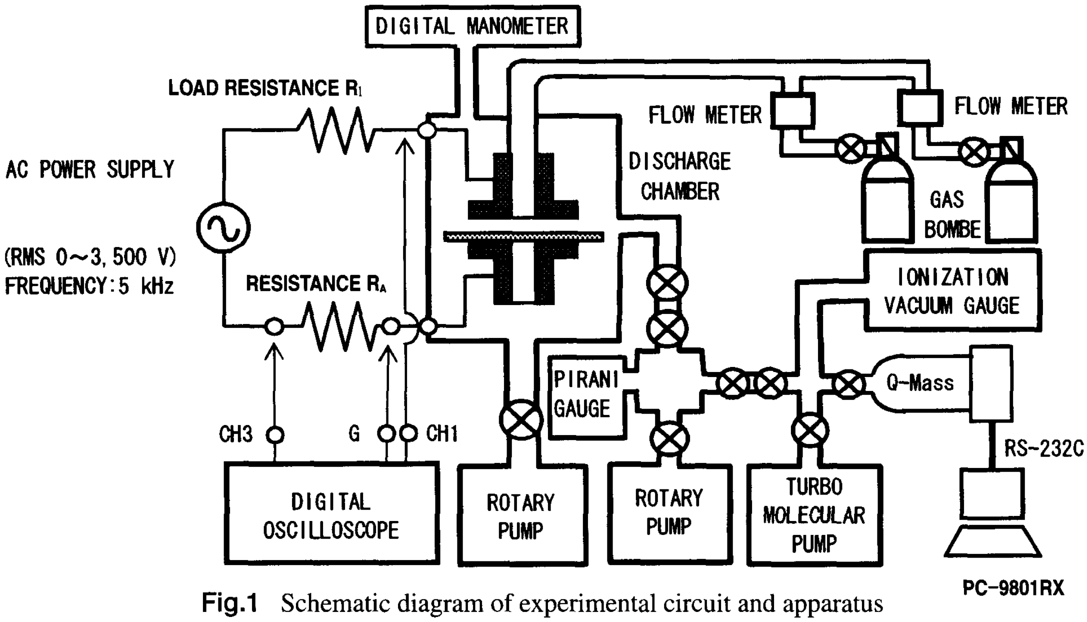


Fig.1 Schematic diagram of experimental circuit and apparatus

are constructed from a chamber, the exhaust systems, the analysis part for NOx gases and the measurement part for discharge wave form.

The power supply is alternative current which is a sine wave and about 5 kHz. Author employs the transformer which is connected the output terminal of power supply, because of adjusting impedance matching between power supply and barrier discharge. The load resistance, R_L, is 20 kΩ and the resistance for current measurement, R_A, is 1 kΩ. A voltage and a current of the experimental circuit are measured by a digital oscilloscope.

The thickness of dielectric substrate, which is hard glass, is 0.15 mm. The gap between electrodes is measured by using the gap gauge and is fixed one value, for example 0.6, 0.9 and 1.05 mm, like as the ratio of the gap between electrodes and the thickness of dielectric substrate is integer. The electrodes are fixed above and below and face to face as shown in Fig.1. The dielectric substrate is put on below side electrode. The electrode has a hole and the gases used in this work are lead to the field of discharge through this hole.

The gas was exhausted from the discharge chamber, after the electrodes and the dielectric substrate were fixed in the chamber, as mentioned above. After this treatment, N_2+NO gas was lead to the chamber until 760 Torr with measuring the pressure in the chamber and the flow rate of gas.

2-2. Experimental Conditions

The experimental conditions are as follows;

(1) Electrode Material : Pt electrode, which has a hole.

Inner diameter: 6 mm, Outer diameter: 15 mm

(2) Dielectric Substrate : Hard Glass, thickness is 0.15 mm, relative permittivity is 6.9

(3) Electrode Gap: 0.6, 0.9, 1.05 mm

(4) Power Supply

Voltage: 0~3,500 volts (RMS)

Frequency: 4.7 kHz

(5) Load Resistance: 20 kΩ

(6) Circumstance Gases

Pressure:700,760 Torr

Experiment 1: N_2+NO (458 ppm, 4502 ppm)

Experiment 2: Mixed Gas of N_2+NO and CH_4

3. Experimental Results

3-1. Results of Phase Difference

Fig.2 is the experimental circuit for the measurement of phase difference. Fig.3 shows waveforms of the terminals a-b and c-b, the terminals a-c and b-c, respectively. The waveform of terminal c-b is as same as the current waveform. As shown in Fig.3, the phase difference, ϕ, between V_{ab} and V_{cb} exceeds to $\pi/2$.Where V_{ab} is the voltage between electrode, and V_{cb} is as same as the current waveform of discharge. In all of the present work, the values of phase difference become larger than $\pi/2$ and the power factor, $\cos\phi$, shows negative value.

Author cannot give the reasonable account except thinking that the part of reactor, which is the

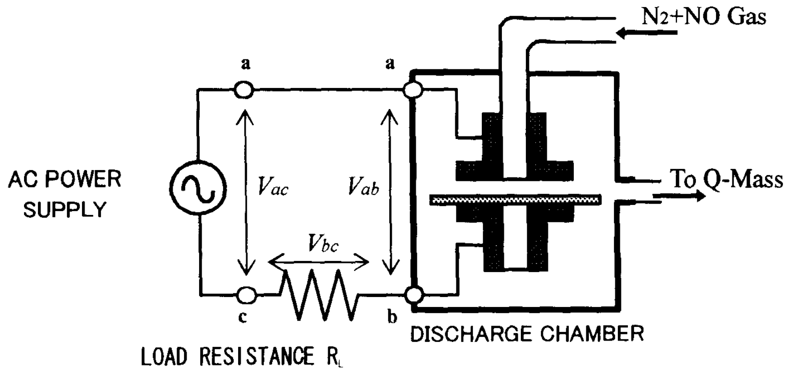
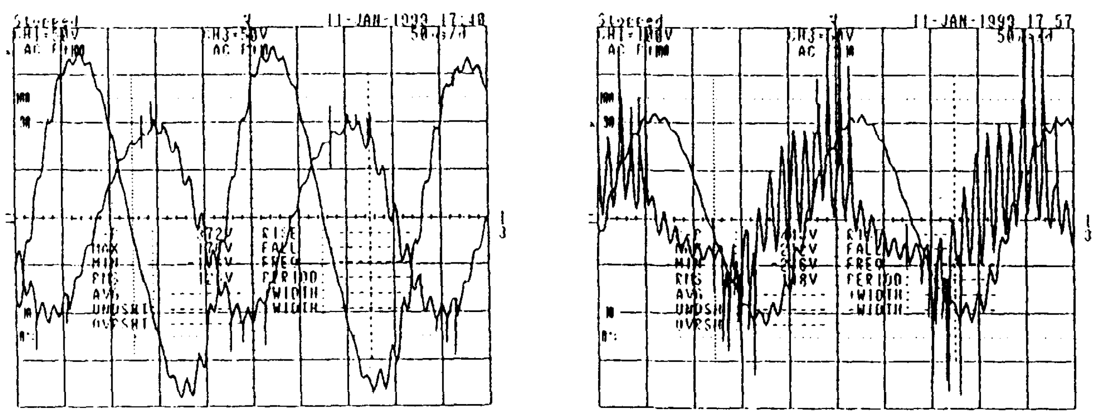


Fig.2 Experimental Circuit



(a) phase difference between V_{ac} and V_{bc} (b) phase difference between V_{ab} and V_{bc}

Fig.3 Waveforms of each terminal

part of discharge, becomes power source apparently in this circuit with involving measurement installment.

3-2. Measurement of Consumed Power by 3-Voltmeters Method

Considering the reactor part as a circuit, author can present the equivalent circuit as shown in Fig.4. In Fig.4, R_r' and C_r' can be neglected in this circuit. So, author presents the new equivalent circuit as the equivalent one for the reactor part.

In Fig.5, we can calculate the power consumed in discharge and the phase difference between the current and the voltage of discharge by measuring three voltages between terminals a-c, b-c and a-b. This method is called "3-Voltmeters Method". Assuming that the reactor part can be presented the equivalent circuit as shown in Fig.5 and each terminal voltage of a-c, b-c and a-b are signed V_{ac}, V_{bc} and V_{ab}, the relationship of theses three voltages can be shown in Fig.6. From this Fig.6, we can express the power consumed in discharge, P, and power factor, $\cos\phi$, by following equations.

$$|V_{ac}|^2 = |V_{ab}|^2 + |V_{bc}|^2 - 2|V_{ab}|\cdot|V_{bc}|\cos(\pi-\phi)$$
$$= |V_{ab}|^2 + |V_{bc}|^2 + 2|V_{ab}|\cdot|V_{bc}|\cos\phi \quad (1).$$

Therefore,

$$\cos\phi = (|V_{ac}|^2 - |V_{ab}|^2 - |V_{bc}|^2)/(2|V_{ab}|\cdot|V_{bc}|) \quad (2).$$

Moreover, power consumed in discharge is shown the following equation;

$$P = |V_{ab}|\cdot|I|\cos\phi \quad (3)$$

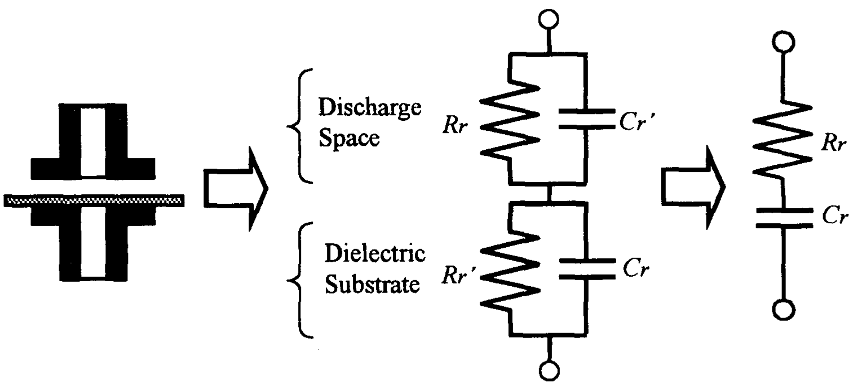


Fig.4 The equivalent circuit of barrier discharge.

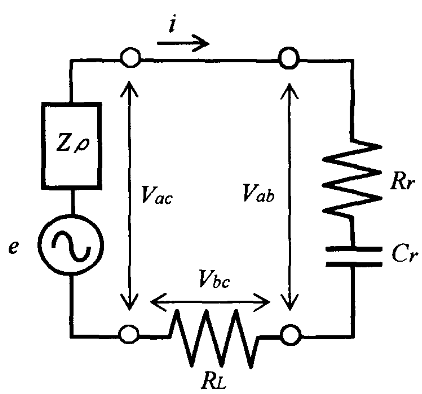


Fig.5 Equivalent circuit of reactor part

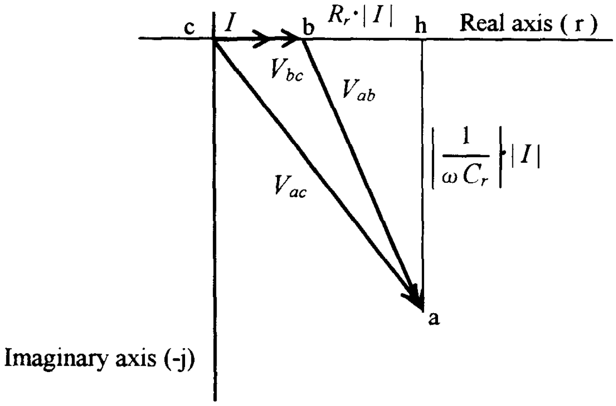


Fig.6 Vector figure of V_{ac}, V_{ab} and V_{bc}

and current is given in Eq. (4)

$$|V_{bc}| = R_L \cdot |I| \qquad (4).$$

Substituting eq.(3) and eq.(4) to eq.(1),

$$|V_{ac}|^2 = |V_{ab}|^2 + |V_{bc}|^2 + 2R_L \cdot |I| \cdot |V_{ab}| \cos\phi$$

$$|V_{ac}|^2 = |V_{ab}|^2 + |V_{bc}|^2 + 2R_L \cdot P \qquad (5)$$

Therefore, we can obtain power consumed in discharge, P.

$$P = (|V_{ac}|^2 - |V_{ab}|^2 - |V_{bc}|^2)/(2R_L) \qquad (6)$$

We can obtain the power consumed in discharge by measuring V_{ac}, V_{ab} and V_{bc}, simultaneously. Table 1 shows results in experiment 1,which is done under the condition of 458 ppm and 4502 ppm in N_2+NO gas. And, Table 2 is results in experiment 2, of which circumstance is mixed gas of N_2+NO and CH_4.

As shown in Table 1-1, 1-2 and Table 2, the power consumed in discharge is not negative in al-

Table 1-1 Results by 3-Voltmeters Method (N_2+NO (458 ppm), R_L = 20 kΩ)

V_{ac} (V)	V_{ab} (V)	V_{bc} (V)	P by 3-V Method (W)
1900	1740	94	14.34
1820	1800	90	1.61
1780	1780	91	-0.21

Table 1-2 Results by 3-Voltmeters Method (N_2+NO (4502 ppm), R_L = 20 kΩ)

V_{ac} (V)	V_{ab} (V)	V_{bc} (V)	P by 3-V Method (W)
2140	1830	113.2	30.45
2240	1860	112.1	38.64
2180	1780	111.4	39.29

Table 2 Results by 3-Voltmeters Method (N_2+NO (4502 ppm) and CH_4, R_L = 20 kΩ)

	V_{ac} (V)	V_{ab} (V)	V_{bc} (V)	P by 3-V Method (W)
No Discharge	1020	572	13.4	17.83
Discharge as Filament	1350	1280	34.0	4.57
Barrier Discharge	2560	2260	54.2	36.08
Complex Discharge	2660	2540	155.0	15.00

most of data. As shown in Table 2, the power consumed in discharge shows the difference in accordance with the situation of discharge. The power is the most consumption in barrier discharge.

3-3. Estimation of R_r and C_r in Barrier Discharge

By using 3-Voltmeters Method, we can estimate the values of the equivalent resistance, R_r, and capacitance, C_r, in barrier discharge. In Table 1-1, let us pick 1820 volts, 1800 volts and 90 volts up as V_{ac}, V_{ab} and V_{bc}, respectively. So, we can draw a vector figure by using three voltages as shown in Fig.6, if the circuit as shown in Fig.5 is supposed as the equivalent circuit. In this figure, the length of h-b means the potential of the terminals of R_r and the length of a-h means the potential of the terminals of C_r. Namely,

$$\left.\begin{array}{l}\text{the length of h-b} = R_r \cdot |I| \\ \text{the length of a-h} = (1/\omega C_r) \cdot |I|\end{array}\right\} \quad (7)$$

Moreover, since the discharge current can be obtained from Eq.(4)

$$|I| = |V_{bc}| / R_L \quad (8),$$

the values of R_r and C_r are calculated following equations.

$$\left.\begin{array}{l}R_r = (\text{the length of h-b}) / |I| = R_L \cdot (\text{the length of h-b}) / |V_{bc}| \\ (1/\omega C_r) = (\text{the length of a-h}) / |I| = R_L \cdot (\text{the length of a-h}) / |V_{bc}|\end{array}\right\} \quad (9)$$

In this work, we employ that ω is $2\pi f$ and f is 4.7 kHz, so we obtain that

R_r is about 64 kΩ, C_r is about 85.6 pF (10).

4. Discussion

Treating that the structure of electrodes is the parallel plane capacitance, this theoretical capacitance, C_{theo}, can be represented in Eq.(11).

$$C_{theo} = (\varepsilon_0 \cdot \varepsilon_r \cdot S) / d \quad (11)$$

Where d is the electrode gap, which is 0.15 mm, ε_0 is the dielectric constant, ε_r is the relative permittivity of hard glass, which value is 6.9 and S is the area of electrode surface. By employing values that d is 0.15 mm, ε_0 is 8.854×10^{-12} (F/m) and ε_r is 6.9, we can obtain the following value of C_{theo}.

$$C_{theo} = 70.8 \times 10^{-12}\ (\text{F}) = 70.8\ (\text{pF}) \quad (12)$$

In comparison with Eq.(10) and Eq.(12), the measurement value of capacitance is in good agreement with the theoretical one.

In the circuit of discharge as shown in Fig.5, the discharge current is shown in Eq.(13).

$$I = E / (Z_p + Z_r + R_L) \quad (13).$$

$$\begin{aligned} Z_p + Z_r + R_L &= (R_p + \mathrm{j}\,X_p) + (R_r - \mathrm{j}(1/\omega C_r)) + R_L \\ &= (R_p + R_r + R_L) + \mathrm{j}(X_p - (1/\omega C_r)) \end{aligned} \quad (14)$$

Where Z_p is the inner impedance of power supply, X_p is the reactance and j is the imaginary unit. Therefore, the maximum value of discharge current must be satisfied the condition as given by Eq.(15).Namely,

$$X_p = (1/\omega C_r) \quad (15).$$

Moreover, the power consumed in reactor is given in Eq.(16)

$$P=|I|^2 \cdot R_r \qquad (16),$$

the maximum power consumed in reactor must be satisfied the following condition.

$$R_p = R_r + R_L \qquad (17).$$

Eqs.(15) and (17) mean the impedance matching of the circuit.

In this work, the output of power supply is connected to the transformer which acts as matching transformer. So, it is considered that the reactance, X_p, of this transformer is mainly inductance, L_p. Therefore, if the inductance is satisfied with Eq.(18) from Eq.(15), the author can obtain the maximum power consumed in discharge.

$$\omega L_p = (1/\omega C_r) \qquad (18)$$

Our experimental apparatus is not satisfied with the condition mentioned above. Because reactance of which inductance of transformer has is larger than that of reactor.

5. Conclusion

(1) The equivalent circuit of the reactor is the series connection of the resistance and the capacitance.

(2) The value of the capacitance of the equivalent circuit is in good agreement with the theoretical value.

(3) It must be employed the reasonable transformer which is satisfied with Eq.(18)to obtain the maximum power consumed in reactor.

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