論 文
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질소 플라즈마의 임피이던스 특성 및 정합회로 설계

Impedance Characteristics of N_2 Plasma and Matching Circuit Design

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요 약

RF방전 시스템을 설계하려면 먼저 그 전기적 특성을 알아야 한다. 따라서 본 논문에서는 실험적 자료에 의존하는 기존의 방법과는 달리 질소플라즈마의 임피이던스를 이론적으로 도출해 내고 이로부터 플라즈마 생성 및 최대전력전송에 필수적인 정합회로를 설계하였다. 또한 설계된 정합회로를 이용하여 질소플라즈마의 임피이던스를 역산해보고 이 값과 앞의 이론치를 비교, 검토함으로써 본 이론의 타당성을 입증할 수 있었다. 마지막으로 부하 임피이던스의 변화량을 감지하여 정합회로내 소자값들을 적정치로 보상해주는 자동정합회로를 설계하였으며 그 실험결과들을 고찰하였다.

Abstract

In the design of an RF discharge system, the electrical equivalence of the gas discharge must be known. With this knowledge, one can design a suitable matching network for a maximum power transfer from the RF generator into the discharge.

For this purpose, an experiment has been conducted in which the electrical impedance (conductance and capacitance)was determined as a function of power. In parallel with this, a detailed theoretical analysis has been done and the results are in accord with those of our experiment. Design equations are also given for a simple matching network, and a design example is presented to demonstrate its application. During the actual operation of an RF discharge system, however, it has been often observed that the reflected power tends to vary in small values due to the changes in the impedance of the system. This problem can be relieved by adding an automatic impedance matching circuit to the system and this paper presents such an automatic impedance matching network.

1. Introduction

It is opten desirable to represent an RF discharge system by an electrical equivalent circuit. This has been tried by Koenig nd Maissel(1970)[1] In this work, their assumption was based on that the plasma attenuates voltage perturbation by forming a sheath, leaving the undisturbed region, i.e. the plasma itself, equipotential and lossless. In our model, however, it is assumed that the plasma has its own conductance and capacitance which consume the RF power, i.e. the plasma itse-

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lf, dielectric medium. We also let the sheath model be not "resistive" but "capacitive" because sheaths in high frequency(i.e., 13.56MHz) plasma are primarily "capacitive" unless the density is large.[2] The impedance of the sheath at the wall, however, is omitted because the chamber wall, made of glass, is not in contact with the plasma in our system.

Consequently, we assume that the circuit model of an RF discharge system consists of the sheath capacitance and the impedance of the plasma. With this model, we can get the whole electric equivalence of RF discharge system by the following method. First, we can figure out the impedance of N_2 plasma from the Langevin equation in which the electron density and temperature are determined by the probe measurements.

Second, we can get the sheath capacitance by assuming that the sheath length is approximately the same order of the Debye shielding length.[3] From this, we can design the matching network which is essential for the ignition of the discharge and a maximum power transfer.

Besides, using this matching circuit and a SWR(Standing Wave Ratio) meter, we can obtain an electrical measurement of the entire glow discharge region between the cathode and anode, including the positive sheath. The comparison between these measurements and our theoretical results will be discussed.

Finally, both an automatic impedance matching circuit and its experimental data will be also discussed.

2. The Impedance Characteristics of N_2 Glow Discharge

At MHz operating frequencies the massive ions cannot follow the temporal variations of the applied potential. However, the electrons can. Thus the cloud of electrons can be pictured as moving back and forth at the applied frequency in a sea of relatively stationary ions. From this point of view, we can use the Langevin equation, which is as follows :

$$\frac{d}{dt}(m\vec{u}) = -e\vec{E} - m\vec{u}\nu_m \tag{1}$$

, where ν_m is defined as the collision frequency for momentum transfer. If we assume that there exist only elastic collisions, the collision frequency is represented by NQU, where N is the density of neutral particles, Q is the collision cross section and U may be considered as the electron thermal velocity. The electric field can be considered to be oscillatory $\vec{E} = \vec{E}_0 e^{j\omega t}$. By substituting this electric field into the equation(1) and from the eq. $\vec{P} = -ne(\vec{u}/j\omega)$.

$$\vec{P} = \frac{ne^2}{j\omega m(\nu_m + j\omega)} \vec{E} \tag{2}$$

By substituting this polarization into the relation $\vec{D} = \varepsilon_0 \vec{E} + \vec{P}$, we can find the permittivity as follows :

$$\varepsilon = \varepsilon_0\left(1 - \frac{\omega_p^2/\omega^2}{1 - j\nu_m/\omega}\right) \tag{3}$$

, where ω_p is the plasma frequency

Therefore, Maxwell equation is written as follows.

$$\begin{aligned} \nabla \times \vec{H} &= \varepsilon \frac{\partial \vec{E}}{\partial t} \\ &= \frac{ne^2 \nu_m}{m(\nu_m^2 + \omega^2)} \vec{E} + j\omega\varepsilon_0\left(1 - \frac{\omega_p^2}{\omega^2 + \nu_m^2}\right)\vec{E} \\ &= \vec{J}' + \frac{\partial \vec{D}'}{\partial t} \end{aligned} \tag{4}$$

From this equation, we can find what may be called "the equivalent conductivity" σ which satisfies the relation $\vec{J}' = \sigma' \vec{E}$ and "the equivalent permittivity" ε' which satisfies the relation $\vec{D}' = \varepsilon' \vec{E}$.

$$\begin{aligned} \sigma' &= \frac{ne^2 \nu_m}{m(\nu_m^2 + \omega^2)} \\ \varepsilon' &= \varepsilon_0\left(1 - \frac{(\omega_p/\omega)^2}{1 + (\nu_m/\omega)^2}\right) \end{aligned} \tag{5}$$

Our generating frequency is 13.56 MHz and its wavelength extends to 22m. Thus we can apply the lumped circuit analysis. An equivalant circuit for the glow discharge is shown in (Fig. 1). The equivalent circuit assumes that the chamber wall is not in contact with the plasma. The sheath capacitances result from the charge separation across the dark space. These capacitors are shunted to the electrode surface by a diode to account for the high electron current that can flow from the plasma to an electrode that is biased positive relative to the plasma potential. In the sheath region, there are only a few numbers of oscillating ions.[4] Thus we can obtain the sheath capacitance by assuming that the sheath length is approximately the same order of the Debye shielding length[3] and that the dielectric constant can be considered as that of vacuum.

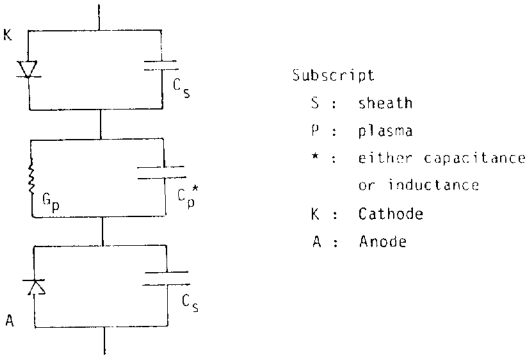

Fig. 1. Euqivalent circuit model of the glow discharge.

If we assume the plasma between the plates is uniform, we can get G_p, C_p and C_s as follows.

$$G_P = \sigma' \frac{S}{l}$$

$$C_P^* = \varepsilon' \frac{S}{l}$$

$$C_S = \varepsilon_0 \frac{S}{l_s} \qquad (6)$$

were S : the area of the plates
l : the gap length between the plates
l_s : sheath length (≧ Debye shielding length)

i. e.

$$l_s \sim \left(\frac{\varepsilon_0 K T_e}{n e^2} \right)^{\frac{1}{2}} \qquad [m]$$

(*) In certain situations, such as in the ionosphere or in a tenuous electronic plasma in our laboratory, the quantity ε' can be negative without any contradiction to the causality principle.[7] In this case the plasma itself can be treated as "inductive" load. Consequently, C_p^* can be either "capacitance" or "inductance", which is determined by the sign of the dielectric constant ε' [8]

3. Matching Circuit Design

The output produced by RF generator can be regarded as a voltage source with its internal impedance of 50 ohm by the method of image impedance. The load impedance, however, can be even higher or lower than the source impedance by the fact that the impedance of N_2 plasma is, as we can see in the equation (5), (6), a function of both electron density and temperature. We, therefore, simulate a load equal to the generator output impedance by combining the discharge load with a variable matching network load. Thus the purpose of the matching network is to introduce inductance into the circuit in such a way that, in combination with the load, they form a resonant circuit.[5]

When the variable matching network components are tuned to resonance, high circulating currents flow within the resonant circuit. However, the power supply sees only the resistive component of the load, and the current passing from the power supply to the resonant circuit is in phase with the load and represents the real power passing to the load. The configuration of our total system including typical L-type matching network is shown in(Fig.2)

If the left side of the dashed line in figure 2 has an internal impedance of a+jb ohms, then a simple calculus argument suggests that the impedance of the right side must be equal to a–jb ohms (i.e., the conjugate of the generator output impedance) for a maximum power transfer. Thus the conjugate impedance is required so that the total load is purely resistive. From this relation, the design

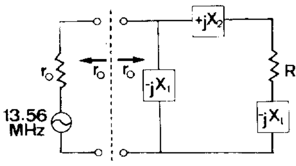

Fig. 2. Matching network.

equations for our L-type network can be easily obtained.

The equations are as follows :

$$X_1 = r_0 \Big/ \left(\frac{r_0}{R_L} - 1\right)^{\frac{1}{2}}$$

$$X_2 = X_L + R_L\left(\frac{r_0}{R_L} - 1\right)^{\frac{1}{2}} \qquad (7)$$

, where X_L : reactive component of load impedance
R_L : resistive component of load impedance
X_1 : total reactance of the shunt branch of the L-network.
X_2 : total reactance of the series branch of the L network
r_0: characteristic impedance of the generator output impedance (usually 50 ohms)

As we can see in the equation(7), X_1 compensates for the difference between the amounts of r_0 and R_L. Similarly, X_2 compensates for the phase shift following with the change of X_L.

Now, the main process of the matching circuit design is as follows. At first, as we should know the electron density and temperature in order to get the load impedance, we have used the Langmuir probe for those measurements. The probe was made of a tungsten wire (0.1mm, 0.3mm length) shielded by glass. The applied bias is −50 V ~ 250 V and the electron saturation current is about 10mA. When the applied RF power is 80W and the pressure is 10 mTorr, the plasma density is 3.73×10^{15} m^{-3} and the electron temperature is 4.72 eV.

Thus from the equation (5), (6), we get the following parameters.

$N = 3.3 \times 10^{20}$ $[m^{-3}]$
$Q = 1.1 \times 10^{-19}$ $[m^2]$
$U(\text{thermal}) = 1.6 \times 10^6$ [m/sec]
$\nu_m = 5.9 \times 10^7$ $[sec^{-1}]$
$\sigma' = 0.58$ [℧/m]
$\varepsilon' = (\quad)0.988 \times 10^{-8}$
$\omega_p^2 = 1.2 \times 10^{19}$
$S = 0.0113$ $[m^2]$
$l = 41$ [mm]
$l_s = 0.83$ [mm]
$G_P = 0.16$ [℧]
$C_P^* = 2723$ [pF]
$C_S = 120.5$ [pF]
$Z_P = 1/(G_P + j\omega C_P^*)$
$= 2.04 + j2.93$ [Ω]

From the relation $Z_L = Z_P r + /j\omega C_s$, we get the following load impedance.

$Z_L = 2.04 - j94.47$ (Ω)

now, by letting the inductance 2.60 μH, we can get the nominal values of shunt and series capacitance as follows :

C (shunt) = 1138[pF]
C (series) = 100[pF]

Thus our designed matching network is as follows :

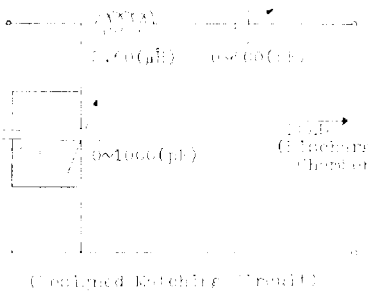

Fig. 3. Designed matching circuit.

4. Comparison between the Theory and the Experiment

By the use of the matching circuit designed in the previous section, we can generate the N_2 plasma and set the amount of SWR to unity. Furthermore, by measuring the amount of the impedance of each matching circuit element just when the value of SWR is set to unity, we can calculate back the impedance of the gas discharge. The result measured under the same condition in section III is as follows :

C (shunt ; measured) = 847[pF]
C (series ; measured) = 100[pF]

From the equation[7], we can obtain the experimental value of the conductance and the capacitance as folows :

G_L (experimental) = 0.430[℧]
C_L (experimental) = 128.5[pF]

These values are seen to be close to the values obtained from our theoretical approach.

G_L (theoretical) = 0.229[℧]
C_L (theoretical) = 124.2[pF]

The comparison of the experimental values with the theoretical velues for the increase of RF power is shown in the following figures.

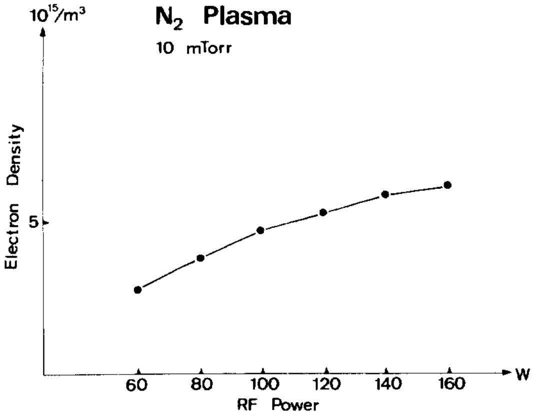

Fig. 4. RF power-electron density relation.

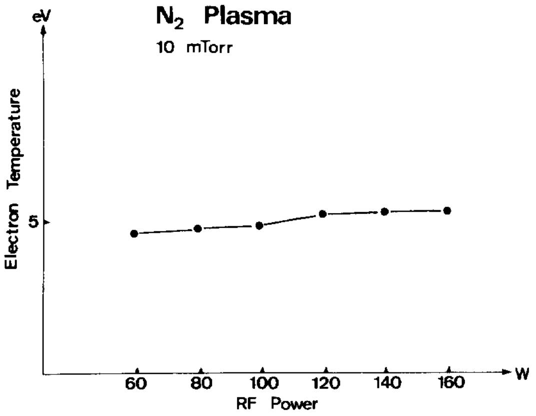

Fig. 5. RF power-electron temperature relation.

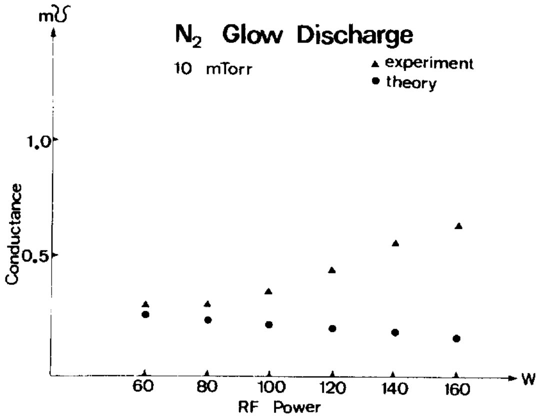

Fig. 6. Conductance of RF discharge system.

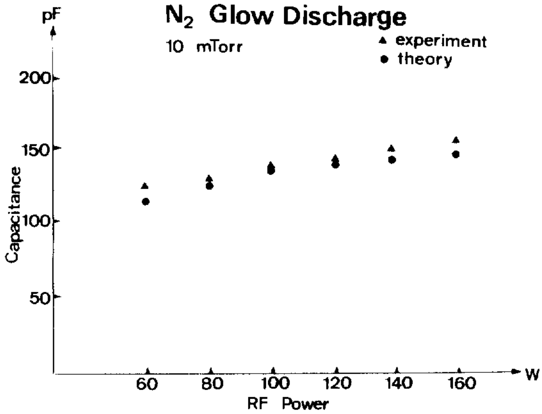

Fig. 7. Capacitance of RF discharge system.

The changes of the electron density and temperature with the increase of RF power is checked through the Langmuir probe measurements and shown in (Fig.4) and (Fig.5). Figure 4 and 5 show that both electron density and temperature increase with RF power and this is because collisions between the electrons and neutral particles increase with power. (Fig.6) shows that the experimental results of the conductance are accord with the theoretical results except at high RF powers and these values are nearly constant because of the fact that the impedance of N_2 plasma is relatively small value in comparison to that of the sheath. (Fig.7) shows that both the theoretical and experimental capacitance of N_2 glow discharge are well in accord with each other and increase with power.

This power dependance is consistant with the fact that the sheath length decreases with increasing power. This argument is quite admissible because the Debye shielding length decreases with increasing density. As another check on our theory and experiment, the electron density and temperature under the same condition in section Ⅷ are obtained from the experimental values of the system impedance.

$$n = 1.769 \times 10^{15} \, [m^{-3}]$$
$$T_e = 3.54 \, [eV]$$

These values are very close to the values obtained from the Langmuir probe measurement. With this encouraging result, we can design the automatic impedance matching network discussed in the following section.

5. Automatic Impedance Matching Circuit

The automatic matching network is designed to transform to the 50 ohms a wide range of resistance and reactive impedance that are encountered during a typical plasma operation.

Thus, the block diagram of the automatic impedance matching unit is shown in (Fig.8).

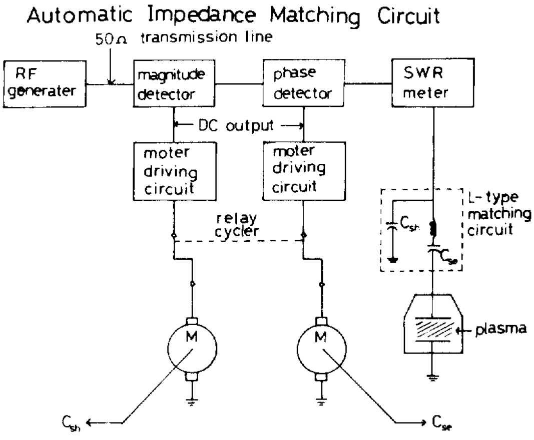

Fig. 8. The block diagram of the automatching circuit.

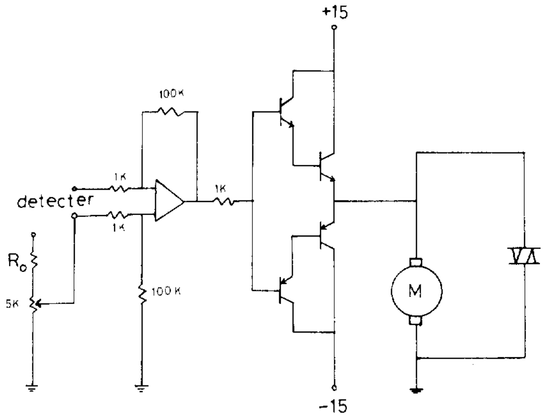

Fig. 9. Servo-amplifier.

Since the load impedance Z_L may be expressed as $Z_L = |Z_L| \angle\theta$, it is necessary only to measure the magnitude and phase angle of the impedance in order to determine it uniquely.

Hense, to monitor the impedance, two conventional detectors[9] are placed in the transmission line. The DC output signals of these detectors are used with servo-amplifier is shown in(Fig.9). The front part of the circuit is differential OP amplifier and the rest is a class B push-pull power amplifier with a Darlington connection.

6. Experimental Results

(1) Experiment 1. (the polarity of the detector output)The polarities of the detector outputs for

Table 1. (*)Correct only in a small variation. (; about 2% of load variation)

Variation		Output polarity	
Shunt Capacitance	Series Capacitance	Magnitude Detector	Phasor Detector
0	0	0	0
+	0	(*) −	0
−	0	+	0
0	+	−	−
0	−	+	+
0 : matched value + : increase − : decrease		0 : no output + : positive − : negative	

various capacitor combinations are given in (Table 1).

(2) Experiment 2.(Individual Automatching)
  a. Variation of the impedance
    : obtained by the deviation of the capacitances in the matching entwork
    b. There is no underdamping.
    c. automatching time : 1–4[sec]

(3) Experiment 3.(Total System Automatching)
  a. Variation of the impedance
    : obtained by varing the pressure or the RF power
  b. relay cycler time : 4–6[sec]
  c. automatching time : 15–45[sec]

7. Conclusion

The electrical impedance of N_2 glow discharge has been determined and this theoretical value has been used to design a matching network. Both the theoretical and experimental impedance of N_2 glow discharge are well in accord with each other. The capacitance of N_2 glow discharge is increased when the RF power is increased but the conductance is not closely related to the power.

An automatic impedance matching network has been described and its experimental results have been discussed.

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