Effect of Magnetic Field on Enhanced Ionization in Magnetron Discharge

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Abstract. The experiment and self-consistent model that clarify the influence of magnetic field on a planar magnetron discharge are described. The results show that the low impedance characteristics of the dense magnetron discharge is caused by enhanced ionization due to the impact of primary electrons, which are accelerated by the cathode fall and trapped magnetically between the cathode and the anode. The effect of non-uniform magnetic field on the magnetron discharge is also discussed.

1. Introduction

The magnetron discharge, one of crossed-field discharges, makes it possible to produce a dense plasma in relatively low pressure gases and it is widely used as the plasma production for the sputtering devices. It is of considerable important to understand the fundamental phenomena in magnetron discharge and there have been a number of models of the magnetron discharge [1,2,3]. However, most of these models are too much complicate to explain the physical meaning, since they deal with the rather special structure of discharge in commercial magnetron devices.

In this paper, we described the experimental results demonstrated the effect of magnetic field on the magnetron discharge using a test device with a variable magnetic field and a movable anode and propose a simplified self-consistent model of the enhanced ionization in the dc magnetron discharge. This model is based on a new concept of the sustaining mechanism of low-pressure glow discharges [4,5,6,7].

2. Experimental result

In order to clear the effect of magnetic field on the discharge characteristics, the experiment is curried out by using a planar magnetron device in which the magnetic field and the electrode separation can be varied [see Figure 1]. The gases used are He and H_2 in the pressure range from 0.15 to 2.0 Torr. The variation of the discharge voltage V_d with the magnetic field strength B is measured under the condition of a fixed discharge current (I_d = 50mA) and various electrode separations (d_{AK} = 5~30mm) at constant gas pressure p. After starting the magnetron discharge, the magnetic field is decreased gradually at fixed discharge current.

The typical characteristics of V_d vs. B are shown in Figure 2. The similar characteristics are obtained in He discharge although V_d is a little higher than that in H_2 discharge. As the magnetic field is decreasing, the discharge mode changes drastically from low impedance to high impedance at a critical value B_C of the magnetic field. The effect appears remarkably in the lower pressure range. In the lower pressure, the discharge without the magnetic field is very high impedance due to weak ionization collisions ($\lambda^* >> d_{AK}$, where $\lambda^* = 1/Q^*$ is mean ionization length of electron impact and Q^* is total ionization cross-section) and is called as the obstructed glow mode. In the higher pressure range ($\lambda^* \gtrsim d_{AK}$), a large current discharge without the magnetic field becomes an abnormal glow mode.

The magnetic field for the magnetron operation is required to satisfy $B > B_C$. The critical magnetic field, B_C, strongly depends on the electrode separation d_{AK} and varies inversely with d_{AK} for $B_C > B^*$ (or $d_{AK} < d^*$) as shown in Figure 3, where B^* and d^* are the values at the inflection of the B_C-d_{AK} curve. The discharge current, gas species and pressure slightly affect on the relationship between B_C and d_{AK}. This fact (the product $B_C \cdot d_{AK}$ is constant) suggests that the primary electrons trapped by the magnetic field cause the enhanced ionization in the magnetron operation.

In the larger electrode separation ($d_{AK} > d^*$), however, B_C is independent of d_{AK} and takes a minimum value B^* of B_C. We also discuss about B^* and d^*, which are determined from the non-uniform distribution of magnetic field, which decreases with the distance from the cathode, and from the structure of electrodes.

3. Simple model of magnetron discharge

3.1 The critical magnetic field for magnetron discharge

Now let us consider the one dimensional, low-pressure and dense glow discharge ($\lambda^* > d_{AK} >> d_{CS}$) in a transverse uniform magnetic field, where λ^* and d_{CS} are mean ionization length of the energetic primary electrons and the cathode sheath thickness, respectively. The conventional theories of the cathode fall are based on the collisional sheath where the electron multiplication is essential. In the dense glow discharge, however, any ionization does not occurs in the cathode sheath because the thickness of cathode sheath is very thin ($d_{CS} << \lambda^*$). The ionization occurs in the plasma column by the impact of primary electrons accelerated up to eV_{CS}, where V_{CS} is the potential drop across the cathode sheath. The thickness d_{CS} of cathode sheath is estimated from Child-Langmuir equation by using V_{CS} and ion current density (Bohm current).

The discharge voltage at fixed current is expressed as $V_d = V_{CS}+\Delta V$, where ΔV (usually $<<V_{CS}$) is the potential drop across the plasma column, and V_d is given by the following formula obtained from the plasma balance equations [5,6,7],

$$V_d = \left(1+\frac{\Delta V}{V_{CS}}\right)V_{CS} \quad , \qquad V_{CS} = \eta\left(\frac{\phi_i}{\gamma}\right)F(n_{et}) \tag{1}$$

where ϕ_i and γ are the ionization potential and the coefficient of γ process, respectively. The factor (ϕ_i/γ) means that the energy gain of a primary electron must be required to be $eV_{CS} = e(\phi_i/\gamma)$ for generating the number $1/\gamma$ of ions, which release one electron from the cathode. This is the self-sustaining condition in the most effective glow discharge when $\eta=1$, $F(n_{et})= 1$ and $\Delta V=0$. The factor η is the ratio among the energy losses of primary electrons, that is (the total energy losses for ionization, excitation and heating plasma electrons and so on)/(the energy loss for ionization), to keep the plasma in steady state. The function $F(n_{et})$ is the reciprocal of trapping factor of primary electrons and expressed as follows,

$$F(n_{et}) = \frac{1}{1-\dfrac{\Gamma_{el}'}{\Gamma_{el}}} \geq 1 \tag{2}$$

where Γ_{el} is the total flux of primary electrons and Γ_{el}' is the flux of primary electrons passing through the plasma column without any ionization. This factor strongly depends on λ^*/d_{AK} in the glow discharge without the magnetic field. In the low-pressure regime ($\lambda^*/d_{AK} >> 1$), $F(n_{et})$ is overly large ($F(n_{et}) >> 1$), and hence the discharge voltage becomes very high (the obstruct glow mode), according to equation (1). If the primary electrons are sufficiently trapped between the electrodes by the magnetic field, $F(n_{et})$ becomes nearly equal to unity and then the low impedance discharge, i.e. the magnetron discharge, is realized. The effect of the magnetic field on ΔV and η is trivial compared with its effect on $F(n_{et})$.

In the case of the uniform magnetic field, no electric field in the plasma column and $d_{CS} <<$ electron cyclotron radius r_{ce}, the trajectory of the primary electron is reflected on the sheath boundary and drifts in the x direction [see Figure 4]. This drift motion of the electron is different from ***E***x***B*** drift [8,9], which usually appears in dilute plasma ($d_{AK} \sim d_{CS} > r_{ce}$) produced by crossed-field discharge. The condition of electron confinement, $F(n_{et}) = 1$, is given by $r_{ce} = (mv/eB) \lesssim (d_{AK} - d_{CS}) \sim d_{AK}$, where v is the electron velocity corresponding to V_{CS}. From this condition, we can easily obtain the product $B_c \cdot d_{AK}$ as follows;

$$B_C.d_{AK} = \left(\frac{m}{e}\right)\sqrt{\frac{2eV_{CS}}{m}} = 3.37\sqrt{V_{CS}} \qquad \text{G.cm} \tag{3}$$

If the particle losses to the wall and in the plasma volume are small and hence there is no need of ohmic heating for additional ionization, the potential drop ΔV is disregarded ($\Delta V << V_{CS}$). Therefore, V_{CS} is nearly equal to V_d and then the equation (3) can be rewritten as $B_C.d_{AK} \approx 3.37\sqrt{V_d(B_C)}$. This agrees well with the experimental results in narrower electrode gap as demonstrated in Figure 3. The discharge voltage at B_C increases slightly with d_{AK}, as shown in Figure 2. This seems to be caused by the increase of ΔV with elongated gap length. However, the effect of V_d on B_c is not so strong, because B_C is proportional to $V_d^{1/2}$.

The critical magnetic field B_C for magnetron discharge is determined from the sufficiently trapping condition of primary electrons emitted from the cathode sheath edge in the magnetic field. If the electrode gap is relatively narrow, B_C is calculated from equation (3), even if the magnetic field is non-uniform. However, this relationship does not hold in longer electrode gap with non-uniform magnetic field. The effect of non-uniformity in magnetic field, that is the appearance of B^*, is discussed in the following section.

The effect of magnetic field below B_C can be explained by introducing following formula,

$$F(n_{et}) = \left\{1 - \exp\left[-\left(\frac{B_c d_{AK}}{B\lambda^*}\right)\sin^{-1}\left(\frac{B}{B_C}\right)\right]\right\}^{-1} \qquad \text{for } B \le B_C \qquad (4)$$

This equation is obtained from the relationship, $\Gamma_{el}' / \Gamma_{el} = \exp[-l/\lambda^*]$, where $l = r_{ce}\sin^{-1}(d_{AK}/r_{ce})$ is path length along the electron orbit from cathode sheath to anode. This equation shows that the magnetic field affects more strongly on the enhanced ionization in the low-pressure range ($d_{Ak}/\lambda^* << 1$).

As the magnetic field increases beyond B_C, the plasma bulk separates into two regions, glowing region ($d_{CS} < x < r_{ce}$) and dark region ($r_{ce} < x < d_{AK}$). The plasma particles are mainly generated in the glowing plasma region by the primary electrons trapped there. The dark plasma plays the role of a conductor to flow the discharge current, which is carried by the plasma electrons (secondary electrons). If the magnetic field is too much stronger than B_C, the electric field is induced in the plasma region (it is due to the decrease of electron mobility in the transverse magnetic field, and E is proportional to B^2). Therefore, the discharge voltage V_d increases with the magnetic field. Moreover, the rotation of plasma bulk might be driven by $\boldsymbol{J}$x$\boldsymbol{B}$ force. It is not appropriate for the usual magnetron operation to apply the excessive magnetic field beyond B_C.

3.2 Effect of non-uniform magnetic field

For simplicity, we consider the motion of electron injected into a transverse magnetic field, $B(y, z=0) = B_0/(1+(y/a)^2)$, induced by a linear dipole array at ($x = \pm\infty, y = 0, z = \pm a$), where $2a$ is the gap length of the dipole and B_0 notes the magnetic field at $y = z = 0$ (see Figure 5). The trajectory of electron motion on the mid-plane is obtained from computer calculation under the various conditions. The electron is emitted at $y = b$ with the velocity $v = (2eV_{CS}/m)^{1/2}$ and turns over at $y = y_T$. Figure 5 shows the distance ($y_T - b$) as a function of a/r_{ce0} and b/a. Here, we regard the parameter b as the location of the cathode surface, because the cathode sheath thickness is very thin. The electron is trapped between the cathode and the anode when (y_T-b) $\lesssim d_{AK}$. If $b << a$, the condition for electron trapping is as follows,

$$\frac{d_{AK}}{r_{ce0}} = \frac{y_T - b}{r_{ce0}} = f\left(a/r_{ce0}, b/a\right) \quad \begin{cases} \sim 1 & \text{for } a/r_{ce0} > 1 \\ > 1 & \text{for } a/r_{ce0} < 1 \end{cases} \qquad (5)$$

The knee of the curve in Figure 5 corresponds to B^* and d^* in Figure 3. We easily obtain $B^* \sim (mv/e)/a$ and $d^* \sim a$. They are in good agreement with the experimental result ($d^* \sim a = 1.25$ cm). It is evident that equation (3) is valid in the non-uniform magnetic field, if half-length a of magnet gap is larger than d_{AK}. J. Goree et al. reported same result from a computer simulation [10]. The appearance of B^* and d^* is found to be caused by the non-uniform magnetic field which decreases rapidly with the distance from the cathode ($\Delta B = B_0 - B(d_{AK}) > (1/2)B_0$).

4. Conclusion

The effect of magnetic field on enhanced ionization in magnetron discharge is investigated experimentally and theoretically. The ionization occurs in the plasma column by collisions between the molecules and the trapped primary electrons, which are accelerated by cathode fall. If the primary electrons are confined magnetically between the electrodes, they spend their all energies on sustaining the discharge. Therefore, we can realize a low-impedance glow discharge, that is the magnetron discharge, in relatively low-pressure range. The magnetron discharge appears in the stronger magnetic field than the critical field B_C, which is determined from equation (3). Equation (3) is derived from the orbital motion of primary electron in the uniform magnetic field and no electric field. It is evident that the equation (3) is valid in the non-uniform magnetic field, if its non-uniformity $\Delta B = B_0 - B(d_{AK})$ is smaller than $(1/2)B_0$ on the mid-plane. It is appropriate that the magnetic field configuration satisfies the following condition; $B > B_C$ and half-length a of the magnet gap $> d_{AK} >>$ distance b from the magnet to the cathode surface.

Three-dimensional confinement of the primary electrons is not discussed here. Most of the conventional magnetron devices use the non-uniform magnetic field whose configuration corresponds to a kind of magnetic mirrors. In the magnetic mirror field, the primary electrons that lost their energies move cross the magnetic field by additional grad-B drift and bounce along field lines between the mirror points. It is easily expected that they are confined in the restricted region determined from the shape of the mirror field.

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Figure captions

Figure 1. Illustration of planar magnetron, which consists of a movable anode, a graphite disc cathode and a magnetic circuit excited by four magnet coils.

Figure 2. Variation of discharge voltage V_d with magnetic field B, when the discharge current is fixed (I_d = 50mA). The magnetic field B is the value on the cathode at the center of the magnet gap.

Figure 3. Relationship between the critical magnetic field B_C and the electrode separation d_{AK}.

Figure 4. Electron drift due to reflection on the cathode sheath boundary (in the case of uniform magnetic field).

Figure 5. Effect of non-uniform magnetic field on the orbital motion of electron; the relationship between the distance $(y_T-b)/r_{ce0}$ and a/r_{ce0}. In the non-uniform magnetic field due to a linear dipole array, an electron (with velocity v) starts from $y = b$ and turns over at $y = y_T$. The variable a/r_{ce0} corresponds to the characteristic magnetic field for the electron, where a and r_{ce0} are the half-length of dipole gap and the electron cyclotron radius for $B(y=0,z=0)$, respectively.

Figure 1.

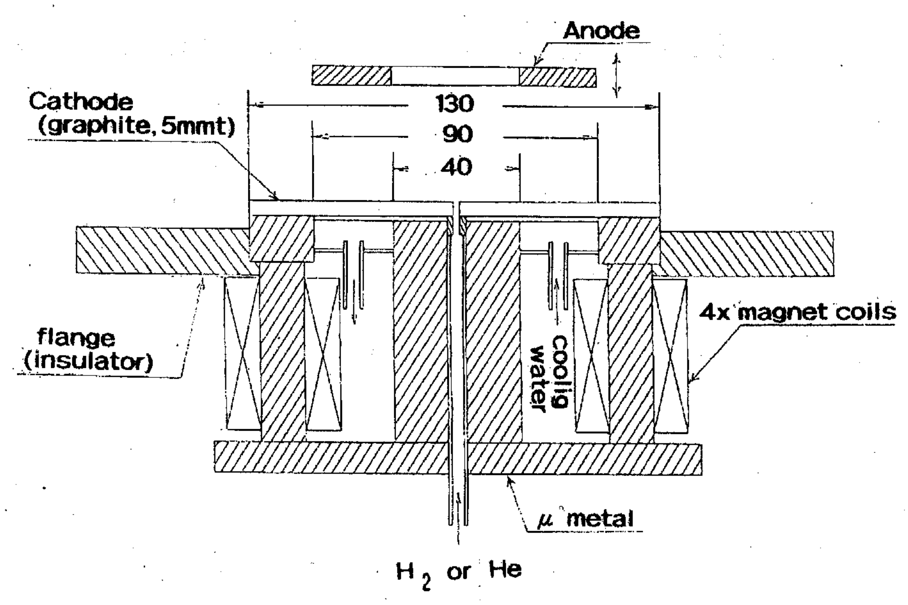
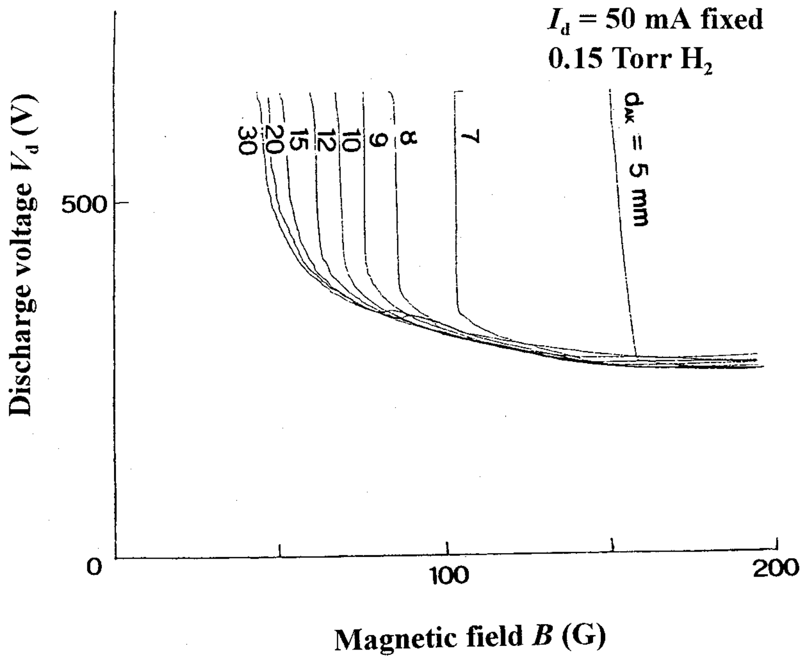

Anode
Cathode
(graphite, 5mmt)
130
90
40
flange
(insulator)
4x magnet coils
coolig
water
μ metal
H 2 or He

Figure 2 .


I_d = 50 mA fixed
0.15 Torr H_2
d_{AK} = 5 mm
7
8
9
10
12
15
20
30
Discharge voltage V_d (V)
500
0
100
200
Magnetic field B (G)

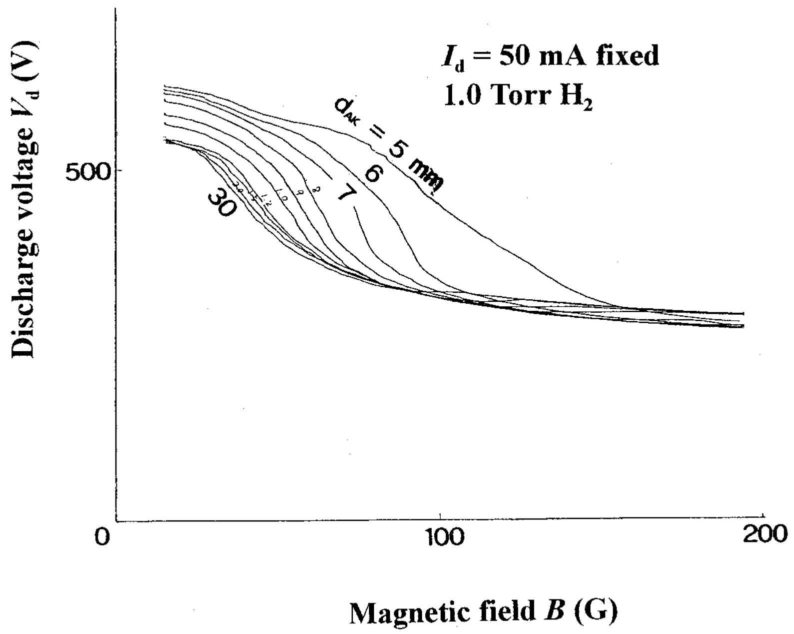

I_d = 50 mA fixed
1.0 Torr H_2
d_{AK} = 5 mm
6
7
30
Discharge voltage V_d (V)
500
0
100
200
Magnetic field B (G)

Figure 3 .

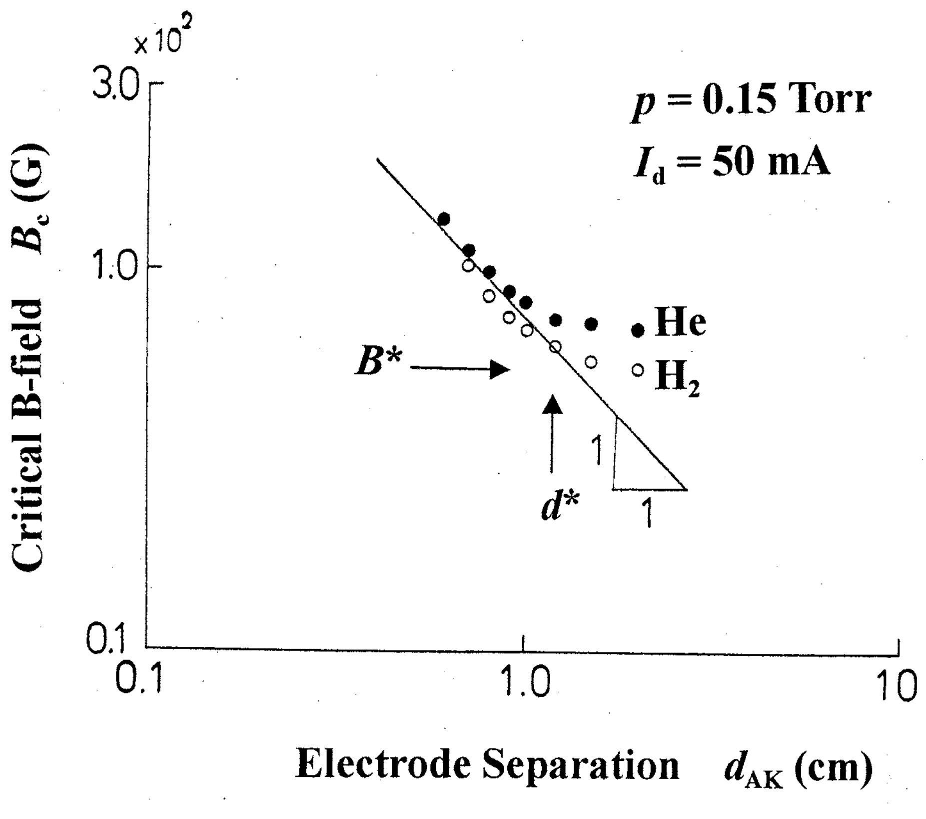

x 10^2
3.0
1.0
0.1
0.1
1.0
10
Critical B-field Bc (G)
Electrode Separation dAK (cm)
p = 0.15 Torr
Id = 50 mA
He
H2
B*
d*
1
1

Figure 4 .

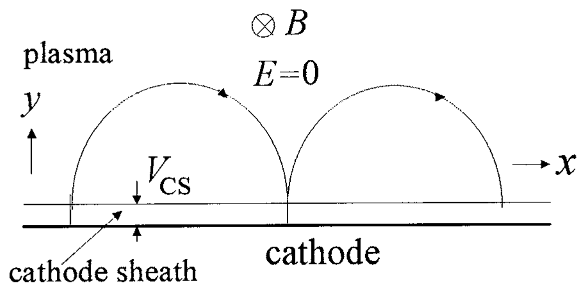
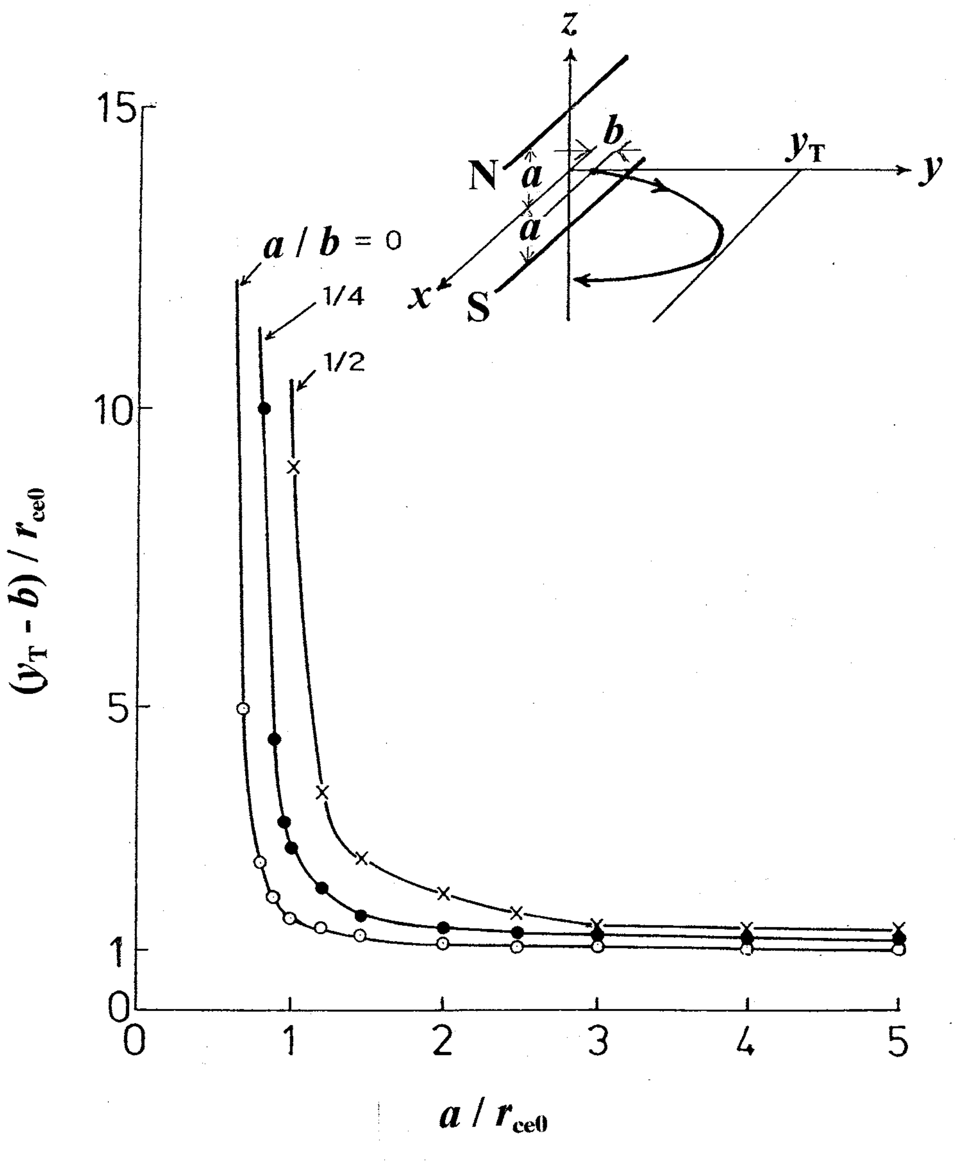


Figure 5.



Appendix

Derivation of equation (1) (reported previously [5,7])

If there is no field in the plasma column (no additional heating σE^2 of plasma electrons), the plasma is kept steady-state (n, T_e = *cosnt*) by the energy input of primary electrons accelerated up to V_c. In the plane geometry, the plasma balance equations are easily expressed as follows,

$$R_i = \left(\frac{\Gamma_i}{L}\right)\left(1 - \frac{R_r}{R_i}\right)^{-1} = R_{loss} \quad (8)$$

$$e\Gamma_{el}V_c\left(1 - \frac{\Gamma'_{el}}{\Gamma_{el}}\right) = e\phi_i R_i\left(1 + \frac{R_\varepsilon \varepsilon}{R_i e\phi_i}\right)L \quad (9)$$

where R_i and R_r are the rates of ionization and recombination, and $R_\varepsilon \varepsilon$ is the rate associated with energy losses except energy loss $R_i(e\phi_i)$ for ionization (e.g. excitation, heating of plasma electrons). The flux Γ_{el}' is the flux of primary electrons passing through the plasma column without any energy loss

Using equations (8) and (9), the sustaining condition of discharge plasma can be written by

$$\frac{\Gamma_{el}}{\Gamma_i} = \gamma = \frac{\phi_i}{V_c}\frac{\left(1 + \frac{R_\varepsilon \varepsilon}{R_i e\phi_i}\right)}{\left(1 - \frac{R_r}{R_i}\right)\left(1 - \frac{\Gamma'_{el}}{\Gamma_{el}}\right)}$$

and then the potential drop V_c is obtained as follows,

$$\left.\begin{aligned} V_c &= \eta\left(\frac{\phi_i}{\gamma}\right)F(n_{et}) \\ \eta &= \left(\frac{1 + \frac{R_\varepsilon \varepsilon}{R_i e\phi_i}}{1 - \frac{R_r}{R_i}}\right) \geq 1 \\ F(n_{et}) &= \frac{1}{1 - \frac{\Gamma'_{el}}{\Gamma_{el}}} \geq 1 \end{aligned}\right\} \quad (10)$$

cf. L in the equations (8) and (9) is the length of plasma column.