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Plasma properties in a high-pressure gas mixture for a plasma display panel

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Abstract. Electrical breakdown in a mixed gas is investigated. The plasma at breakdown is evaluated in terms of the mole fraction χ. The optimum condition for the highest plasma density is described in terms of the ionization energy and collisional cross-section of the mixed gas. The optimum mole fraction for the highest plasma density is found to be $\chi = 0.03$ for the case of plasma generation in neon gas mixed with xenon for a plasma display panel. The optimum condition for the highest number of electronic excitations is also obtained.

1. Introduction

The estimate of the plasma density at an electrical breakdown is one of the important issues in applications of various electrical discharge plasmas in high-pressure gas. As an example, we consider the electrical discharge system in a high-pressure inert gas in connection with its applications to the plasma display panel (PDP) [1–3]. Reduction of the breakdown voltage in a low-pressure gas by the Penning effect was reported previously [4], where 0.01% of argon gas is mixed with neon. However, the plasma display panel is operated at high-pressure, and the breakdown voltage reduction in a mixed gas is mostly accomplished by collision-frequency decrease, as will be seen later. The ultraviolet light emitted from a xenon discharge plasma is converted into fluorescence, which provides an image on a television screen. The discharge plasma is generated by the electrical breakdown. Reduction of the discharge voltage and plasma-density increase are the key elements in enhancing the electrical efficiency of PDPs. The electrical efficiency enhancement in turn prolongs the panel lifetime. The radius of the xenon atom is relatively large, so that electrons in the plasma are highly collisional. Therefore the electron mean free path is small in xenon gas, requiring a high breakdown voltage. Plasma generation in a mixture of xenon and light-atom gases may not require a high breakdown voltage. Moreover, the low ionization energy and the large ionization cross-section of xenon may provide a high plasma density. We therefore investigate the electrical discharge properties in order to obtain a simple scaling law for electron density and atomic excitation in a mixed gas. The operating conditions in PDP cells depend on the system parameters adopted by various manufacturers of PDPs. For example, the operating pressure of PDP cells is in the range of 300–500 Torr. The neon–xenon mixture gas consists of 4% of xenon and 96% of neon. Some cells are operated with a tri-mixed gas, which consists of 70% of helium, 27% of neon and 3% of xenon. The typical electrode width of PDP cells is 300 μm and the gap distance between electrodes is 100 μm.

The properties of the plasma density at breakdown in a mixed gas are investigated in Sec. 2 based on the electron rate equation. The estimation of ion density is carried out, and it is shown that the ions consist mostly of heavy atoms, due to low ionization energy and large ionization cross-section. An expression for its plasma density, (16), is obtained in terms of the gas mixture ratio. It is also found from (16) that the maximum plasma density occurs at the mixture ratio $\chi = \chi_m = T_0/\zeta\epsilon_X$, (18), where T_0 is the electron breakdown temperature of a single-species gas, ζ is the relative ratio of the scattering cross-section and ε_X is the ionization energy of heavy atoms. As an example, we consider plasma generation in neon gas mixed with xenon. The parameter ζ in this mixed gas is $\zeta = 11$. The typical value of the single-species temperature T_0 in this mixed gas is $T_0 = 3.9$ eV. The ionization energy of xenon is $\epsilon_X = 12.2$ eV. Substituting these numbers into (18), we find that the optimum value of the mixture ratio for the highest plasma density is $\chi_m = 0.03$ for neon gas mixed with xenon.

Some of the excited atoms return to the ground state, emitting photons. The accumulated number N^* of excitation occurrences, (28), of heavy atoms in unit volume is estimated in Sec. 3 based on the rate equation of atomic excitation. This number equation is described in terms of the gas mixture ratio χ. Differentiating the accumulated excitation number N^* with respect to the mixture ratio χ, we obtain the optimum condition (32) for the highest number of excitation occurrences. As an example, we consider xenon excitation in neon gas mixed with xenon. The optimum mixture ratio for the highest excitation number is $\chi = T_0/\zeta\epsilon_X = 0.03$, which is also the optimum mixture ratio for the highest plasma density.

2. Properties of plasma density in a high-pressure gas mixture

The mean free path λ of electrons in the mixed gas is inversely proportional to the product of the scattering cross-section and the neutral number density:

$$\frac{1}{\lambda} = [\sigma_N(1-\chi) + \sigma_X\chi]n_n = 2.5 \times 10^{19}[\sigma_N(1-\chi) + \sigma_X\chi]p, \tag{1}$$

where σ_N, and σ_X denote the scattering cross-sections of species N and X, respectively, and p is the gas pressure in units of atmospheres. In (1), χ denotes the mole fraction of the gas species X. The electrons are accelerated by an electric field E, and gain a kinetic energy of λeE before they collide with neutrals. These slow elections are scattered isotropically in collisions with molecules, thermalizing their gained energy. This process repeats until they establish their temperature $T = \xi\lambda eE$, where ξ is the thermalization form factor of electron energy. The thermalization form factor ξ is expressed as $\xi = v_{\rm th}/2v_d$ for $v_{\rm th}/v_d \gg 1$ typical for high-pressure discharges. Here $v_{\rm th}$ and v_d are the thermal and drift velocities respectively of electrons. Therefore the electron temperature is proportional to the product of the mean free path λ and the electric field E, and is expressed as

$$\frac{1}{T} = 2.5 \times 10^{19}\frac{\sigma_N p}{\xi E}[1 + \zeta(T)\chi], \tag{2}$$

where the ratio ζ of the scattering cross-sections is defined by

$$\zeta(T) = \frac{\sigma_X - \sigma_N}{\sigma_N}. \tag{3}$$

The electron temperature in (2) is well known and corresponds to the Druyvesteyn energy distribution [5]. The breakdown voltage $V_b = Ed$ is calculated from (2), and can be expressed in terms of the breakdown temperature T_b by

$$\xi V_b = 2.5 \times 10^{19} \sigma_N T_b [1 + \zeta(T_b)\chi] pd. \tag{4}$$

We refer the reader to the review [6] for further information on the breakdown voltage in terms of the mole fraction χ.

The analytical description of plasma density is based on the electron moment equation

$$\frac{\partial n_e}{\partial t} + \frac{\partial}{\partial z}(v_d n_e) = \alpha n_e - \frac{D}{\Lambda^2} n_e - \alpha_r n_e^2, \tag{5}$$

where n_e is the electron density and α is the ionization rate of neutrals by electrons. In (5), the term proportional to D is the diffusion loss of electrons, where Λ is the plasma size, and the term proportional to α_r, is the recombination loss of electrons. The characteristic ionization time of the first term on the right-hand side of (5) is $1/\alpha$. The ionization time of a neon plasma is 30 ns for an electron temperature $T = 3$ eV. Before breakdown, the characteristic time of recombination is of the order of milliseconds. In this context, we may neglect the electron loss by diffusion and recombination.

Even for a small system such as a PDP cell, electrons collide with neutrals far more than 100 times before they reach the anode. The electron drift velocity v_d in (5) is related to the thermal velocity, which is almost constant along the axial (z) direction. Moreover, the thermal velocity of electrons is much larger than their drift velocity. The electrons are highly collisional in a high-pressure gas typical in PDP cells. Thus, it is expected that the electron energy in a PDP cell is in a Maxwellian distribution. Assuming that the electron energy is in a Maxwellian distribution and that the electron temperature T is much less than the ionization energy ϵ_i, the ionization rate α is expressed as an simple exponential function of temperature [7]. Therefore the electron rate equation in a mixed gas is expressed as

$$\begin{aligned} \frac{dn_e}{dt} &= \frac{\partial n_e}{\partial t} + v_d \frac{\partial n}{\partial z} = \alpha n_e \\ &= 5 \times 10^{19} n_e \frac{p}{\sqrt{\pi}} v_{\text{th}} \left[(1-\chi) q_N \epsilon_N \exp\left(-\frac{\epsilon_N}{T}\right) + \chi q_X \epsilon_X \exp\left(-\frac{\epsilon_X}{T}\right) \right], \end{aligned} \tag{6}$$

where use has been made of the property that the electron temperature is much less than the ionization energy. In (6), $\alpha(T)$ is the ionization rate for a mixed gas, and q_i and ϵ_i are respectively the ionization cross-section increment in units of $\text{cm}^2\,\text{eV}^{-1}$ and the ionization energy in units of eV of species i. In obtaining (6), we have neglected the term proportional to $n_e \partial v_\text{d}/\partial z$ because of the rapid thermalization of electrons at high pressure. Making use of the ionization rate $\alpha(T)$ in (6) and eliminating the electron temperature T in favor of the parameter E/p in (2), we can obtain the Paschen curve of the breakdown voltage for a mixture gas in PDP cells. The breakdown voltage obtained theoretically from the ionization rate α in (6) for a mixture gas agree remarkably well with experimental data [6]. We remind the reader that the ionization rate α in (6) has been obtained for a Maxwellian energy distribution of electrons.

The electric field E in the discharge chamber is an increasing function of time t until it reaches the breakdown field E_b. The electron temperature T increases with the electric field. Therefore, the electron temperature $T(t)$ increases from zero to the temperature T_b at breakdown, as time goes by. Assuming that the electrical breakdown time is τ_b the electron temperature T is related to time t by

$$\frac{t}{\tau_b} = \left(\frac{T}{T_b}\right)^{\eta}, \tag{7}$$

where the power η represents the risetime of the electrical pulse in the system. The ratio T/T_b rises more quickly with increasing t, as the value of the power η increases. In other words, the value of the index η increases as the electrical pulse risetime decreases. Carrying out the time integration in (6) from zero to the breakdown time and changing the integration variable from time t to temperature T, we obtain

$$Y(n_e,\chi) = \ln\left[\frac{n_e}{n_0(z)}\right] = 2.1\times 10^{27}\frac{p\tau_b}{\sqrt{\pi}}\left[(1-\chi)q_N\epsilon_N^{3/2}f\left(\frac{T_b}{\epsilon_N}\right) + \chi q_X\epsilon_X^{3/2}f\left(\frac{T_b}{\epsilon_X}\right)\right], \tag{8}$$

where the integral function $f(y)$ is defined by

$$f(y) = \eta y^{-\eta}\int_0^y x^{\eta-1/2}\exp\left(-\frac{1}{x}\right)dx. \tag{9}$$

In (8), the initial electron density $n_0(z)$ has been assumed to be a function of its position z. The integration variable x in (9) is defined by $x = T/\epsilon$, where ϵ_i is the ionization energy of species i. Equation (8) with (9) is one of the main results of this article, and can be used to determine the plasma density at electrical breakdown for a broad range of system parameters, including the gas ionization cross-section q_i, ionization energy ϵ_i, gas pressure p, discharge time τ_b, the integral function $f(y)$ and the gas mixture ratio χ. Equation (9) can be used to evaluate $f(T_b/\epsilon_N)$ and $f(T_b/\epsilon_X)$ in terms of the electron temperature at breakdown, and the index η related to the electrical pulse risetime as defined in (7).

The integral function $f(y)$ has been investigated in detail in terms of the normalized breakdown temperature y [7]. As expected, the value of the function $f(y)$ increases significantly as the electron temperature at breakdown increases. This increase is almost exponential for a small value of electron temperature that makes $y \ll 1$. We also note that the value of the function $f(y)$ increases significantly as the power parameter η increases [7]. For small values of the electron temperature satisfying $y \ll 1$, the integral function $f(y)$ is almost proportional to the index η. Due to the factor $\exp(-1/x)$, the integrand in (9) approaches zero very quickly as the variable x approaches zero. Moreover, it is a rapidly increasing function of x. Therefore, we recognize the inequality.

$$f(y) \leqslant \frac{1}{2}\eta\sqrt{y}\exp\left(-\frac{1}{y}\right), \tag{10}$$

which agrees with the numerical evaluation of (9) [7]. The right-hand side of (10) is the area of the triangle bounded by $x = 0$ and the upper limit of integration.

After substituting (10) into (8), the logarithm $Y(n_e,\chi)$ of the plasma density is

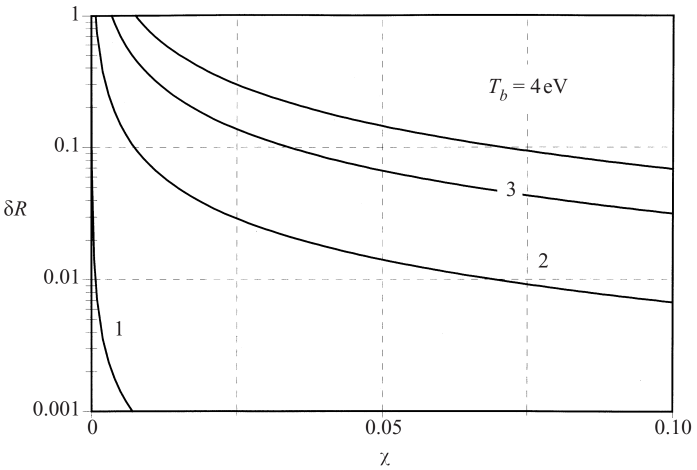

Figure 1. Plot of the remainder δR versus the mixture ratio χ of xenon in neon gas obtained from (12) for several different values of the electron temperature T_b. The parameter $q_X\epsilon_X/q_N\epsilon_N$ in neon mixed with xenon is given by $q_X\epsilon_X/q_N\epsilon_N = 14.7$. The ionization energies for these gas species are given by $\epsilon_N = 21.5\,\mathrm{eV}$ and $\epsilon_X = 12.2\,\mathrm{eV}$.

expressed approximately as

$$Y(n_e,\chi) \leqslant 10^{27}\frac{p\tau_b}{\sqrt{\pi}}\sqrt{T_b}\eta\chi q_X\epsilon_X \exp\left(-\frac{\epsilon_X}{T_b}\right)(1+\delta R), \tag{11}$$

where the remainder δR is defined by

$$\delta R = \frac{1-\chi}{\chi}\frac{q_N\epsilon_N}{q_X\epsilon_X}\exp\left(-\frac{\epsilon_N-\epsilon_X}{T_b}\right). \tag{12}$$

Figure 1 shows a plot of the remainder δR versus the mole fraction χ of xenon in neon gas, obtained using (12) for several different values of the electron temperature T_b. On the basis of documented data [8], the factor $q_X\epsilon_X/q_N\epsilon_N$ is estimated to be 14.7 in a mixture of xenon in neon. The ionization energies for these gas species are given by $\epsilon_N = 21.5\,\mathrm{eV}$ and $\epsilon_X = 12.2\,\mathrm{eV}$. Remember that the remainder δR in (12) is the fractional contribution from neon ionization to the plasma density. Figure 1 shows that the remainder δR is much less than unity except in the range of very high electron temperature and very low mole fraction. The plasma contribution from neon ionization can be neglected, and the plasma density is described only in terms of physical parameters of the xenon gas. In this regard, the plasma density in (11) is further simplified to

$$Y(n_e,\chi) \leqslant 10^{27}\frac{p\tau_b}{\sqrt{\pi}}\sqrt{T_b}\eta\chi q_X\epsilon_X \exp\left(-\frac{\epsilon_X}{T_b}\right). \tag{13}$$

Comparing (6) and (13), we note that the right-hand side of (13) is almost proportional to dn_e/dt.

We now find the plasma density for a specified breakdown voltage V_b. Defining the single-species temperature T_0 by

$$T_0 = \frac{\xi V_b}{2.5\times 10^{19}\sigma_N pd}, \tag{14}$$

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(4) is expressed as

$$\frac{1}{T_b} = \frac{1}{T_b}(1 + \zeta\chi). \tag{15}$$

Note from (15) that the electron breakdown temperature T_b is close to the single-species temperature T_0 for a small value of the mole fraction, which is typical of most PDP applications. After substituting (15) into (13) and eliminating the breakdown temperature T_b, we obtain the approximation

$$Y(n_e, \chi) \leqslant 10^{27} \frac{p\tau_b}{\sqrt{\pi}} \sqrt{T_0}\eta\chi q_X \epsilon_X \exp\left[-\frac{\epsilon_X}{T_0}(1 + \zeta\chi)\right], \tag{16}$$

which is the expression for the plasma density for a fixed voltage.

Note from (16) that the plasma density is described in terms of the mole fraction χ. It is often very useful to find the optimum mole fraction at which the plasma density in (16) has its maximum value. Differentiating Y in (16) with respect to χ, we have

$$\frac{\partial}{\partial\chi} Y(n_e, \chi) = 0, \tag{17}$$

which is satisfied at

$$\chi = \chi_m = \frac{T_0}{\zeta\epsilon_X}. \tag{18}$$

The plasma density for a given breakdown voltage has its maximum value at the mole fraction $\chi = \chi_m$ satisfying (18). As an example, we consider plasma generation in neon gas mixed with xenon. The parameter ζ in this mixed gas is calculated to be $\zeta = 11$ on the basis of documented data [9, 10]. A typical value of the single-species temperature T_0 for neon gas can be calculated from the sparking criterion [7, 11]. For example, when $\xi = 3$, $pd = 0.1$, and the secondary emission coefficient $\gamma = 0.2$, we find $T_0 = 4\,\text{eV}$. The ionization energy of xenon is $\epsilon_X = 12.2\,\text{eV}$ from documented data [8]. Substituting these numbers into (18), we find that the optimum value of the mole fraction for the highest plasma density is $\chi_m = 0.03$ for neon gas mixed with xenon.

The influence of metastable states is a very important in electrical discharges. We briefly consider the influence of the Penning effect on the ionization rate α in (6). The plasma density in (13) is modified by the normalized corrections associated with the Penning effects given by

$$\delta_p = 1.88 \times 10^{-2} \frac{1 - \chi}{\chi} \exp\left(-\frac{4.42}{T_b}\right), \tag{19}$$

which is much less than unity for a mole fraction of $\chi = 0.03$ or more. In obtaining (19), we have used the excitation cross-section increment $q_N^* = 4.3 \times 10^{-19}\,\text{cm}^2\,\text{eV}^{-1}$ and excitation energy $\epsilon_N^* = 16.62\,\text{eV}$ for neon [12]. Taking into account the correction in (19), the optimum mole fraction χ in (18) for the maximum plasma density is modified

$$\chi = \chi_m = \frac{T_0}{\zeta\epsilon_X} - 2.5 \times 10^{-2} \exp\left(-\frac{4.42}{T_b}\right), \tag{20}$$

The last term in (20) originates from the Penning effect. The typical breakdown temperature of electrons for a mixture ratio $\chi \approx 0.03$ is about $T_b = 2.25\,\text{eV}$. In this context, the correction associated with the Penning effect is less than 10% in determining the optimum mixture ratio. The Penning effect is obviously negligible for the parameters in the range of optimum PDP operation. We have therefore neglected the Penning effect in obtaining the optimum condition in (18) for the plasma density.

3. Optimum condition for high-number atomic excitation

The electron density in (6) at time t can be approximately expressed as

$$n_e(t) = n_0 \exp\left[10^{27} \frac{p\tau_b}{\sqrt{\pi}} \sqrt{T} \eta \chi q_X \epsilon_X \exp\left(-\frac{\epsilon_X}{T}\right)\right], \tag{21}$$

where n_0 is the local electron density at $t = 0$. In obtaining (21), use has been made of the time dependence of the electron temperature in (7). Note that, as shown in Fig. 1, the xenon plasma dominates over the neon plasma for the electron temperature $T(t)$ satisfying $T \leqslant T_b$, which is also consistent with (7) before the breakdown time τ_b. In this context, the electron density in (21) is a good approximation for its time evolution. Xenon atoms are excited by collision of electrons. Some of them are in the excited level with the excitation energy of 8.45 eV. Remember that these excited atoms return back to the ground state, emitting 147 nm ultraviolet light, which is used for the television image. It is therefore useful to estimate the number of excited xenon atoms in this level. The rate equation of the excited xenon atoms with excitation energy 8.45 eV is given by

$$\frac{dN^*}{dt} = \alpha_x n_e, \tag{22}$$

where N^* represents number of occurrences of xenon excitation per unit volume and α_x is excitation rate. Note from (22) that the number of excitation occurrences is proportional to the electron density n_e.

Xenon atoms are excited by collision of electrons having energy higher than the excitation energy 8.45 eV. Therefore, the excitation cross section σ_x may be approximated by

$$\sigma_x(\epsilon) = \begin{cases} q^*(\epsilon - \epsilon^*) & (\epsilon > \epsilon^*), \\ 0 & (\epsilon < \epsilon^*), \end{cases} \tag{23}$$

where ϵ is the electron energy, $\epsilon^* = 8.45$ eV is the excitation energy and q^* has units of $\text{cm}^2\,\text{eV}^{-1}$. The excitation rate α_x in (22) can be calculated from (23). Substituting the excitation cross-section α_x, in (23) into the evaluation of the excitation rate,

$$\alpha_x(T) = n_X \int_0^\infty \sigma_x(\epsilon) v g(\epsilon)\, d\epsilon, \tag{24}$$

and assuming a Maxwellian energy distribution of electrons, the excitation rate α_x can be calculated to be

$$\alpha_x(T) = 5 \times 10^{19} \chi p \frac{v_{\text{th}}}{\sqrt{\pi}} q^*(\epsilon^* + 2T) \exp\left(-\frac{\epsilon^*}{T}\right), \tag{25}$$

which is proportional to the xenon mole fraction χ. In (24), n_X, is the neutral-xenon number density. The electron temperature T is typically much less than the excitation energy ϵ^* during the electrical pulse defined in (7).

Substituting (21) and (25) into (22), the rate of increase of the number N^* of excitation occurrences in unit volume is expressed as

$$\frac{dN^*}{dt} = 5 \times 10^{19} n_0 p \frac{v_{\rm th}}{\sqrt{\pi}} q^* \chi \epsilon^* \exp\left[10^{27} \frac{p\tau_b}{\sqrt{\pi}} \sqrt{T} \eta \chi q_X \epsilon_X \exp\left(-\frac{\epsilon_X}{T}\right) - \frac{\epsilon^*}{T}\right], \quad (26)$$

which is zero at $T = 0$, and increases exponentially as the electron temperature T increases. The time integration of (26) can be carried out by changing the integral variable from time t to temperature T according to (7). Integration of (26) over the temperature T is very complicated. However, the right-hand side of (26) has substantial value only when the electron temperature T is close to the breakdown temperature T_b, which is still much less than the excitation energy ϵ^*. In this regard, we can use an approximation similar to (10), which is nothing but the triangular area bounded by $T = 0$ and $T = T_b$. After carrying out a straightforward algebraic manipulation with (7) and (26), we obtain

$$N^* \leqslant 10^{27} n_0 \frac{p\tau_b}{\sqrt{\pi}} q^* \epsilon^* \sqrt{T_b} \eta \chi \exp\left[10^{27} \frac{p\tau_b}{\sqrt{\pi}} \sqrt{T_b} \eta q_X \epsilon_X \chi \exp\left(-\frac{\epsilon_X}{T_b}\right) - \frac{\epsilon^*}{T_b}\right], \quad (27)$$

where use has been made of an expression similar to (10) for analytical simplicity. Note that the excitation density N^* in (27) is almost proportional to its time derivative at $T = T_b$ in (26). Substituting the electron breakdown temperature T_b in (15) into (27), we obtain

$$N^* \leqslant 10^{27} n_0 \frac{p\tau_b}{\sqrt{\pi}} q^* \epsilon^* \sqrt{T_b} \eta \chi \ \exp\left[10^{27} \frac{p\tau_b}{\sqrt{\pi}} \sqrt{T_b} \eta q_X \epsilon_X \chi \exp\left(-\frac{\epsilon_X}{T_0} - \frac{\epsilon_X}{T_0} \zeta \chi\right) - \frac{\epsilon^*}{T_0}(1 + \zeta\chi)\right]. \quad (28)$$

Differentiating N^* in (28) with respect to χ, we obtain

$$\frac{\partial}{\partial \chi} N^*(\chi) = 0, \quad (29)$$

which leads to

$$1 - \frac{\zeta \epsilon^*}{T_0} \chi + A\left(1 - \frac{\zeta \epsilon_X}{T_0} \chi\right) \chi = 0, \quad (30)$$

where A is defined by

$$A = 10^{27} \frac{p\tau_b}{\sqrt{\pi}} \sqrt{T_b} \eta q_X \epsilon_X \exp\left(-\frac{\epsilon_X}{T_b}\right). \quad (31)$$

The temperature T_0 in (30) is the electron breakdown temperature in a single-species gas. The mole fraction χ that solves (30) is the optimum mixture ratio for the highest number of excitation occurrences of gas species X. The solution to the quadratic equation (30) is expressed as

$$\chi = \frac{1}{2\zeta\epsilon_X}\left(T_0 - \frac{\zeta\epsilon^*}{A}\right) + \sqrt{\frac{1}{4\zeta^2\epsilon_X^2}\left(T_0 - \frac{\zeta\epsilon^*}{A}\right)^2 + \frac{T_0}{A\zeta\epsilon_X}}. \quad (32)$$

The terms proportional to A in (30) are contributions from the ion density buildup, and the rest of the terms originate from the neutral density concentration of gas species X. If the constant A in (30) is much larger than ζ, the solution to (30) is almost identical to (18), and, therefore, the excitation of gas species X is achieved by the plasma intensity. On the other hand, the high concentration of gas species X is the cause of the high number of excitations if the constant A is much less than ζ. In this case, the optimum mixture ratio χ for highest excitation number is given by

$$\chi = \frac{T_0}{\zeta \epsilon^*}, \tag{33}$$

for $A \ll \zeta$, which can easily be satisfied for low electron temperature T_b.

As an example, we consider xenon excitation in neon gas mixed with xenon. The parameter ζ in this mixed gas for the temperature range of interest is $\zeta = 11$. A typical value of the single-species temperature T_0 in this mixed gas is $T_0 = 4\,\mathrm{eV}$, as mentioned earlier. The electron breakdown temperature T_b in this mixed gas is about 2.25 eV. Substituting $\eta = 2$, $q_X = 3.12 \times 10^{-17}\,\mathrm{cm^2\,eV^{-1}}$, $\epsilon_X = 12.2\,\mathrm{eV}$, $\tau_b = 300\,\mathrm{ns}$ and $p = 1$ into (31), we find $A = 425$, which is much larger than $\zeta = 11$. Therefore, the optimum mixture for the highest excitation number is $\chi = T_0/\zeta\epsilon_X = 0.03$, which is also the optimum mixture for the highest plasma density.

4. Conclusions

Electrical discharge properties in a mixed gas have been investigated. The properties of plasma density at breakdown in a mixed gas were investigated in Sec. 2 based on the eletron rate equation. The ion density was estimated, and it was shown that the ions are mostly those of the heavy atom due to the low ionization energy and large ionization cross-section. An expression for the plasma density, was obtained in terms of the gas mixture ratio. It was also found from (16) that the maximum plasma density occurs at a mixture ratio $\chi = \chi_m = T_0/\zeta\epsilon_X$, (18). As an example, we considered plasma generation in neon gas mixed with xenon, and found that the optimum value of the mixture ratio for the highest plasma density is $\chi_m = 0.03$ for neon gas mixed with xenon.

The accumulated number N^* of excitation occurrences, (28), of heavy atoms in unit volume was estimated in Sec. 3 based on the rate equation of atom excitation. Differentiating the accumulated excitation number N^* with respect to the mixture ratio χ, we obtained the optimum condition (32) for the highest number of excitation occurrences. As an example, we considered xenon excitation in neon gas mixed with xenon, and found that the optimum mixture ratio for the highest excitation number is $\chi = T_0/\zeta\epsilon_X = 0.03$, which is also the optimum mixture ratio for the highest plasma density.

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