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Abstract

In this paper, we focused on the identification of the normal and abnormal glow discharge modes in a neon-xenon gas mixture at low pressure. We considered four gas mixtures: 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe at 1.5 Torr. The range of the gap voltage is 150–500 V. A one-dimensional fluid model with multiple species was used in this work, and the metastable state of the atoms as well as the radiation effects were integrated into the model too. The input data changed for each percentage in the gas mixture, and was calculated by BOLSIG+ software. The parameters of particle transport and their rate coefficients strictly depend on the mean electron energy. The results show that the neon ion density is negligible compared to the xenon ion density, mostly in the case of 50%Ne-50%Xe.

Keywords: gas mixtures, Boltzmann’s equation, Poisson’s equation, Blanc’s law, two-order fluid model

(Some figures may appear in colour only in the online journal)

1. Introduction

Glow discharge technology [1–6] is an important domain in the microelectronic industry, such as in etching or the deposition of thin solid films, as well as analytical spectroscopy for metallic and sputtering treatment. This technology is used in a lot of pure and mixed gases, but the material technologies which are used in the experimental setup vary from one to another, mostly in the cathode material, which directly influences the current–voltage characteristics. To give some results on the electric discharge, in this paper we propose the study of a neon-xenon DC glow discharge at low pressure with a high percentage of gas in the mixture. By utilizing a fluid model we can find the electrical and energetic characteristics in each mixture, but the problem is related to the type and the percentage of gas in each one. To give the best results using a fluid model, which are in good agreement with the experimental results, it is necessary to know several conditions.

In the research papers [7–10], we find that the electron energy distribution function (EEDF) can be Maxwellian at a very low pressure, and is related to the type of gas. The EEDF is non-Maxwellian for a threshold pressure value, and is again related to the type of gas. Determining the percentage of gas in the mixture is related to the ion mass.

Experiments on the gas mixture have been carried out extensively. For example, the addition of H2 in a Ne-Xe mixture was studied by Wei et al [11], showing an increasing current present in the discharge. Panchenko et al [12] studied the glow discharge in low-pressure excilamps, showing the effect of spontaneous radiation and the effect of halides in mixtures of inert gases, which generated the excited molecules KrCl*, XeCl*, and XeF*. Hassouba and Mehanna [13] studied a N2-H2 gas mixture DC glow discharge at different pressures and electrode separations using a Langmuir single probe. They showed that the electron energy distribution function has a Maxwellian distribution in the positive column, and is a non-Maxwellian form in the cathode fall and negative glow regions.

The objective of this paper is to identify normal and abnormal glow discharge modes at low pressure in 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures. In section 2, the model is described by the quantities (β, α), which represent the percentage of the gas in the mixture. In
section 3, the results are discussed. Finally, a working conclusion is given in section 4.

2. Mathematical model

In order to validate the local EEDF assumption, which is used in this work, we are going to calculate the energy relaxation length as expressed as follows:

\[
\lambda = 2D_e \left( \nu_e + \frac{2m_e}{M_{Ne}} \nu_{Ne} + \frac{2m_e}{M_{Xe}} \nu_{Xe} + \nu_{Xe}^* + \nu_{Xe}^* \right)^{-0.5}
\]

The total collision frequency (\(\nu_t\)) and the electron diffusion coefficient (\(D_e\)) are calculated using BOLSIG+ software [14]. Figure 1 represents the energy relaxation length as a function of the mean electron energy for four gas mixtures. We remark that the energy relaxation length is less than the inter-electrode spacing (1 cm). This remark confirms our assumption of the local EEDF.

The chemical reactions intervening in the discharge are identical, as mentioned in [7]. Firstly, the process of the elastic collision of each gas intervenes in the discharge, and is described by the chemical reaction R1

\[
A + e^- \to A + e^-,
\]

where A plays the role of both neon and xenon gas, and the coefficient \(P_{ec}^A\) related to this process is the energy loss per electron and is calculated according to [15]. Note that \(P_{ec}^A\) is in eVs\(^{-1}\) units. The ionization process is described by reaction R2

\[
A + e^- \to A^+ + 2e^-,
\]

and the ionization coefficient of each gas is \(K_{io}^A\), which depends on the mean electron energy and is calculated using BOLSIG+ software [14]. The excitation process is explained by reaction R3

\[
A + e^- \to A_m^* + e^-,
\]

in which the subscript \(m\) is the metastable state of each gas. In this work, a metastable level of neon of \(2p^53s\) was considered [16] and a \(^3P_2\) level was considered for xenon [17]. The corresponding excitation coefficient is \(K_{exc}^A\) and was determined by BOLSIG+ software [4]. The de-excitation process is defined according to reaction R4

\[
A_m^* + e^- \to A + e^-,
\]

where the corresponding de-excitation coefficient is \(K_{dex}^A\) and is calculated by BOLSIG+ software [14]. Note that \(K_{io}^A\), \(K_{exc}^A\) and \(K_{dex}^A\) are in cm\(^3\)s\(^{-1}\) units. The chemo-ionization process, which intervenes in our discharge, is defined by reaction R5

\[
A_m^* + A_m^* \to A^+ + e^- + A,
\]

where the related chemo-ionization coefficient is \(K_{ch}^A\) is taken from \(4.8 \times 10^{-10}\) cm\(^3\)s\(^{-1}\) [17] of xenon and is equal to \(3.6 \times 10^{-10}\) cm\(^3\)s\(^{-1}\) [18] of neon. The radiation process is defined as follows:

\[
A_m^* \to A + h\nu,
\]

where \(\nu\) is the absorbing photon frequency and \(h\) is the Plank’s constant. By this reaction we can define the metastable lifetime of a gas as \(\tau_{m}^A\) which is equal to \(2.7 \times 10^6\) s\(^{-1}\) of xenon [19] and takes about \(2 \times 10^{-3}\) p s with p in Torr of neon [16]. The stepwise ionization process in our discharge is described by the following reaction:

\[
e^- + A_m^* \to A^+ + 2e^-.
\]

The latest chemical reaction as considered in our discharge is described as follows:

\[
Ne_m^* + Xe \to Xe^+ + e^- + Ne,
\]

and the related coefficient is named as chemo-ionization-de-excitation—i.e. the chemo-ionization process of xenon and the de-excitation process of neon is labeled as \(K_{ch}^{NeXe}\) and is equal to \(7.5 \times 10^{-11}\) cm\(^3\)s\(^{-1}\) [21]. Note that metastable Xe...
cannot ionize the Ne atom, because the energy of $Xe^{m}_{\text{ne}}$ is less than the energy of $Ne^{+}$.

The mathematical model is based on the first three moments of the Boltzmann equation, which are coupled with Poisson’s equation; the metastable atom equation is also included in the model. Then, a description of the model is given by equations (1) to (25). Note that the difference between the existing model and the model given by [7, 8] is devoted to the presence of both $\alpha$ and $\beta$ percentages of the gas as well as the positive ion mobility of each gas in the mixture. Table 1 represents a description of the different notations utilized in the present model.

\[
\begin{align*}
\frac{\partial n_e}{\partial t} + \frac{\partial \varphi_e}{\partial x} &= S_e, \\
\frac{\partial n_{Ne}}{\partial t} + \frac{\partial \varphi_{Ne}}{\partial x} &= S_{Ne}, \\
\frac{\partial n_{Xe}}{\partial t} + \frac{\partial \varphi_{Xe}}{\partial x} &= S_{Xe}, \\
\frac{\partial n_{m}}{\partial t} + \frac{\partial \varphi_{m}}{\partial x} &= S_m, \\
\frac{\partial n_{gas}}{\partial t} + \frac{\partial \varphi_{gas}}{\partial x} &= S_{gas}, \\
S_{Xe} &= n_e (\beta n_o K_{Xe} - n_{Xe} K_{Xe}^{+} - n_{Xe} K_{m_{+}io}), \\
-2n_{m} K_{Xe} &= -2\beta n_{m} n_{Xe} K_{Xe}^{+} - n_{Xe} K_{m_{+}io} - n_{Xe} K_{m_{-}io}.
\end{align*}
\]

Table 1. Description of the different notations utilized in our model.

<table>
<thead>
<tr>
<th>Notations</th>
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<tbody>
<tr>
<td>$n_e$</td>
<td>Electron density</td>
<td>$\varepsilon_{\text{gas}}$</td>
<td>Energy loss of ionized atoms of a gas</td>
</tr>
<tr>
<td>$n^{+}$</td>
<td>Positive ion density of a gas</td>
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<td>Energy gain of chemo-ionization processes of a gas</td>
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<tr>
<td>$n_{Xe}$</td>
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<td>Positive ion flux of a gas</td>
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<td>$\varphi_{Xe}$</td>
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<td>$S_e$</td>
<td>The source term of the energy equation</td>
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<tr>
<td>$\varepsilon_{e}$</td>
<td>Electron flux</td>
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<td>$\varepsilon_{e}$</td>
<td>Electron source term</td>
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<td>$\varepsilon_{e}$</td>
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<td>$\mu_{e}$</td>
<td>Energy loss of excited atoms of a gas</td>
<td>$\mu_{e}$</td>
<td>The electron mobility</td>
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<tr>
<td>$D_{gas}$</td>
<td>The positive ion mobilities of a gas in the mixture</td>
<td>$D_{gas}$</td>
<td>The positive ion diffusion coefficient of a gas in a mixture</td>
</tr>
<tr>
<td>$D_{gas}$</td>
<td>The diffusion coefficient of electrons</td>
<td>$\alpha$ and $\beta$</td>
<td>The percentage of gas in the mixture</td>
</tr>
<tr>
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<td>The gas mixture temperature</td>
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<td>The Boltzmann constant</td>
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<tr>
<td>$\mu_{e}$</td>
<td>The mobility of electron energy</td>
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</tr>
<tr>
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<td>The electron mass</td>
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<td>$e-e$ collision frequency</td>
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<td>$v_{gas}$</td>
<td>Elastic e-atom collision frequency</td>
<td>$\nu_{gas}$</td>
<td>Inelastic e-atom collision frequency</td>
</tr>
<tr>
<td>$\nu_{e}$</td>
<td>Total collision frequency</td>
<td></td>
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</tr>
</tbody>
</table>

\[
S_{m}^{Xe} = n_{e} (\beta n_o K_{Xe} - n_{Xe} K_{Xe}^{+} - n_{Xe} K_{m_{+}io}), \\
-2n_{m} K_{Xe}^{+} = -2\beta n_{m} n_{Xe} K_{Xe}^{+} - n_{Xe} K_{m_{+}io} - n_{Xe} K_{m_{-}io}.
\]

The flux expressions of a particle are given as follows [22, 23]:

\[
\begin{align*}
\varphi_{e} &= -n_{e} \mu_{e} E = -\frac{\partial D_{m} n_{e}}{\partial x}, \\
\varphi_{Xe} &= -n_{Xe} \mu_{Xe} Xe^{+} E = -\frac{\partial D_{m} n_{Xe} Xe^{+}}{\partial x}, \\
\varphi_{m} &= n_{m} \mu_{m} Xe^{+} E = -\frac{\partial D_{m} n_{m} Xe^{+}}{\partial x}, \\
\varphi_{gas} &= -D_{gas} \frac{\partial n_{gas}}{\partial x}.
\end{align*}
\]
The gas ion mobility in the mixture is determined according to equation (22). Table 2 represents the drift velocity and the mobility of a positive gas ion in the gas, $w_{Ne}^{Ne}$ is given by a mathematical expression as a function of the reduced electric field by Frost [24]. $w_{Ne}^{Ne}$ is developed according to the results given by Piscitelli et al [25]. Equation (23) is used to calculate the positive ion diffusion coefficient of a gas in the mixture. Note that the parameter and the mobility of a positive xenon ion $\alpha$ and $\beta$, values in the mixture. For example, the point $\alpha = 0.26$ for neon in the mixture, and the neon ion density is negligible compared to the xenon ion density for an elevated percentage of xenon in the mixture. This is due to the threshold ionization of xenon. This phenomenon is also observed in paper [7]. To conclude, the current–voltage characteristics in 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures, with $T_1 = 7 \times 10^{-5}$ s, $T_2 = 3.6 \times 10^{-5}$ s and $T_3 = 6 \times 10^{-5}$ s, which each represent the maximum time of the simulation, and also represent the steady state of the discharge.

3. Results and discussion

Figure 3 represents the current–voltage characteristics in 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures, with $T_1 = 7 \times 10^{-5}$ s, $T_2 = 3.6 \times 10^{-5}$ s and $T_3 = 6 \times 10^{-5}$ s, which each represent the maximum time of the simulation, and also represent the steady state of the discharge.
The maximum values of the neon and xenon metastable atom densities as a function of the electric potential in the 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures at a pressure of 1.5 Torr. We note that the metastable xenon atom density is superior to the metastable neon atom density due to the threshold excitation of each gas, in which the threshold excitation of xenon is less than the threshold excitation of neon. We remark that the percentage (β, α) of gas in the mixture as well as the applying voltage are highly consequent on the metastable atom densities, which increase with the electric potential. This is due to the augmentation of the electric field, which causes a lot of excitation collisions. We note that both the curves of the neon and xenon metastable atom densities are separate in the range of the applied voltage, mostly in the percentage of neon gas inferior to 90%.

Figure 4 represents the maximum values of the neon and xenon metastable atom densities as a function of the electric potential in the 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures at a pressure of 1.5 Torr.

The electric field at the cathode as a function of the electric potential in the 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures at a pressure of 1.5 Torr. We observe that the electric field increases with the augmentation of the electric potential; this is clearly evident when we utilize the formulation of the gradient of the electric potential. Note that the electric field increases with the percentage of xenon gas due to the threshold ionization.

Figure 5 represents the electric field at the cathode as a function of the electric potential in the 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures at a pressure of 1.5 Torr. We conclude an important remark, namely that the mean electron energy decreases with an increase of the percentage of xenon (β) for a range of voltages, and the mean electron energy increases with the increase of the percentage of xenon for another range of voltages. As an example for the range (>250 V), we remark that the mean electron energy in the 90%Ne-10%Xe gas mixture is superior to the mean electron energy in the 50%Ne-50%Xe gas mixture. Furthermore, for the range (<250 V), the mean electron energy in the 50%Ne-50%Xe gas mixture is superior to the mean electron energy in the 70%Ne-30%Xe gas mixture. These observations are related to the type of glow discharge mode, i.e., in the normal glow discharge mode, the mean electron energy increases with the percentage β, and in the abnormal glow discharge mode the mean electron energy decreases with the augmentation of the percentage β.

Figure 6 represents the maximum values of the mean electron energy as a function of the electric potential in the 90%Ne-10%Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures at a pressure of 1.5 Torr. We note that the effect of the percentage (β, α) of the gas in the mixture is negligible in the range (>400 V). This is due to the value of the potential, which is sufficient to ionize each gas. In view of this figure, we conclude an important remark, namely that the mean electron energy decreases with an increase of the percentage of xenon (β) for a range of voltages, and the mean electron energy increases with the increase of the percentage of xenon for another range of voltages. As an example for the range (>250 V), we remark that the mean electron energy in the 90%Ne-10%Xe gas mixture is superior to the mean electron energy in the 50%Ne-50%Xe gas mixture. Furthermore, for the range (<250 V), the mean electron energy in the 50%Ne-50%Xe gas mixture is superior to the mean electron energy in the 70%Ne-30%Xe gas mixture. These observations are related to the type of glow discharge mode, i.e., in the normal glow discharge mode, the mean electron energy increases with the percentage β, and in the abnormal glow discharge mode the mean electron energy decreases with the augmentation of the percentage β.

4. Conclusion

By applying the fluid model method, we have identified the normal and abnormal glow discharge modes in 90%Ne-10% Xe, 80%Ne-20%Xe, 70%Ne-30%Xe and 50%Ne-50%Xe gas mixtures.
mixtures at a pressure of 1.5 Torr. The results show that the mean electron energy increases with the increase of the percentage of xenon gas in the mixture in the normal glow discharge mode. In the abnormal glow discharge mode, the mean electron energy decreases with the increase of the percentage of the xenon gas in the mixture. Finally, these results present a range of references in the literature, which will help to ameliorate the present model in the future.

References