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Discharge efficiency in high-Xe-content plasma display panels

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We study theoretically the overall output performance and the dominating reaction processes of the vacuum ultraviolet (UV) radiation production in high-Xe partial pressures in plasma display panels (PDPs) with Ne–Xe gas mixtures. A two-dimensional self-consistent fluid model is applied for the simulations of discharges and UV radiation in sustaining phases of PDPs. The UV intensity increases with the Xe partial pressure ($P_{Xe}$). The discharge efficiency also increases with $P_{Xe}$. The resonant radiation from Xe ($^3P_1$) dominates for 3.5%, while that from Xe (1$^3Σ_π^+$) becomes dominant over Xe ($^3P_1$) for 10%–30%. Remarkably for 30%, the intensity from Xe (1$^3Σ_π^+$) is even larger than that from Xe ($^3P_1$). It is found that for higher $P_{Xe}$, the UV radiation mainly consists of the excimer radiation from Xe (1$^3Σ_π^+$) and Xe (3$^3Σ_u^+$). Here, Xe (3$^3P_1$) does not play a role itself as the UV radiator of the resonant radiation (147 nm), but as the precursor to Xe (1$^3Σ_π^+$), which results in the excimer radiation (173 nm). © 2004 American Institute of Physics. [DOI: 10.1063/1.1641961]

I. INTRODUCTION

The plasma display panel (PDP) is regarded as the most promising candidate for the next generation of consumer-oriented, large-size, flat displays. The major trend of the discharge scheme in PDPs is alternating current (ac), capacitive discharges between coplanar electrodes covered by dielectric materials in Xe–noble gas (He, Ar, and Ne) mixtures. Vacuum ultraviolet (UV) radiation from Xe and its excimers from the discharge is converted to visible light by phosphors, in order to display color images. In spite of elaborate efforts in research and development, considerably lower luminous efficiency, approximately by four times than that of cathode-ray-tube displays, is currently a bottleneck of PDP technology in competing against other display technologies in consumer markets. Drastic improvement of the luminous efficiency is the major and urgent objective in PDP technology.

The luminous efficiency of PDPs is given by the following four factors: (1) The discharge efficiency (hereafter, we will refer to it as $η_{dis}$), i.e., the yield of applied electric energy into UV photon energy via discharges (<5%), (2) the probability of the UV photons to be captured by phosphor (~40%), (3) the quantum efficiency of phosphors (~25%), and (4) the yield of the visible photons reaching the display area (~40%), where the percentages in brackets indicate the estimated efficiencies of each factor. Factors 2 and 4 mostly depend on the geometry of PDP cells. A relatively large Stokes shift (from ~143–173 nm to visible wavelength range ~400–700 nm) of the photon conversion scheme using UV radiation limits the quantum efficiency of factor 3 to as low as 25%. Nonetheless, the values are comparable to that in other gas-discharge light sources using similar schemes of visible photon generation. Regarding factors 2 and 4, a drastic improvement in luminous efficiency has been achieved by increasing the effective luminous areas in PDP cells. The discharge efficiency $η_{dis}$ is, on the other hand, extremely small compared with those of other discharges (~65% in a Hg–rare-gas lamp and ~60% in a Xe–DBD lamp), and is mainly responsible for the low luminous efficiency of PDPs. It has been clarified that the significant dissipation of the input power to ions and subsequently to neutrals is the major cause for the low $η_{dis}$ in conventional PDPs with Xe–Ne and Xe–He gas mixtures. This is unfortunately an intrinsic feature of cathode-fall dominated discharges, in general, which are the typical discharges generated in conventional PDP cells. A sufficiently large ion flux to a cathode for emitting secondary electrons is inevitable to sustain the discharges. Recently, it was reported that PDPs with high-Xe-content gas mixtures have the potential for improving luminous efficiency under a conventionally used driving scheme. The luminous efficiency exhibits a step-wise increase by increasing the sustain voltages especially for higher-Xe contents. The luminous efficiency increases linearly to total pressure. Almost all of the UV radiation consists of Xe excimer emission, not of Xe resonance radiation.

In this article, we study theoretically a Xe–Ne ac-PDP for various Xe contents and describe the decisive physical process of the discharge efficiency improvement in high-Xe-content PDPs. We apply a two-dimensional, self-consistent fluid model to analyze the discharge efficiency $η_{dis}$ in a PDP cell. A focus is on the analysis of the reaction chemistry related to the UV generation. The physical description of gas discharges, and numerical techniques implemented in the two-dimensional fluid model, has been described in detail elsewhere. We apply a boundary condition that correctly takes into account of the contribution from the secondary electron flux. The reaction processes considered in the simulation are listed in Refs. 4 and 13. The imprisonment
effect of the Xe resonant line (147 nm) is taken into account in the simulation by introducing the escape factor\(^\text{15}\) for the resonant radiation, which is preliminarily determined by the photon Monte Carlo simulation.\(^\text{16}\) A standard cell structure widely used for ac-color PDPs is considered here. Simulations are performed in a two-dimensional area of the intersection of the sustain electrodes. A schematic geometry of the cell is depicted in Fig. 1. It consists of two glass plates, separated by a gap of 150 \(\mu\)m, filled with a Ne–Xe gas mixture. A pair of electrodes to sustain discharges (hereafter, sustaining electrodes) is placed on the front panel (at the bottom in Fig. 1). The sustaining electrodes are covered by a dielectric layer consisting of a glass plate (dielectric constant \(\varepsilon=11.0\)) and MgO layer at the top (dielectric constant \(\varepsilon=11.0\)). The total pressure of the gas fillings is kept constant at 450 Torr. The partial concentration of Xe \(Xe\) is varied from 3.5%–30%. We first apply a high voltage of 400–500 V between the sustaining electrodes to generate a preliminary discharge. Surface charges that initiate following discharges between the sustaining electrodes are built up on the dielectric layers. Then, discharges are sustained by applying a 50 kHz square ac voltage \((V_s)\) to the sustaining electrodes. We will refer to these discharge periods as sustaining phases. The rise and decay times of \(V_s\) are typically set at 50 ns. Hereafter, we will restrict our discussions to the phenomena in the sustaining phases. The simulations are done all over on the two-dimensional cross section of Fig. 1. Toward the aim of investigating the output performance of the PDP cell, all the results presented here are integrated and averaged in a half cycle and over the cross section, unless it is otherwise mentioned.

II. OVERALL PERFORMANCE

Figure 2 shows the electric input energy \((W_{in})\) per half cycle of the sustaining phase as a function of \(V_s\) for \(P_{Xe}=3.5\%–30\%\). The \(W_{in}\) is linear to \(V_s\) and independent from \(P_{Xe}\). Our preliminary simulation has also found a well-known relation that \(W_{in}\) is approximately proportional to the capacitance \((C_{sus})\) of the sustaining electrode. For the discharge conditions in this article, \(W_{in}\) is then given as a simple relation: \(W_{in} = A \cdot C_{sus} \cdot (V_s - V_{min})\), where \(A\) and \(V_{min}\) are a constant value and a certain minimum voltage \((\sim 140–170\ V)\), respectively. It is noted that a variation with regard to \(V_s\) therefore corresponds linearly to that with regard to \(W_{in}\).

Figure 3 schematically depicts the atomic and molecular electronic states involved in the UV radiation. Except negligibly weak emission from Ne, the UV radiation from PDPs with a Ne–Xe mixture consists of an atomic resonant radiation, \(Xe (^{3}P_1) \rightarrow Xe (^{1}S_0)\), and molecular radiation from three excimers, \(Xe_2 (^{3}Σ_u^+, ^{1}Σ_u^+, O_u^+) \rightarrow Xe_2 (^{1}Σ_g^+) \approx Xe (^{1}S_0) + Xe (^{1}S_0)\).

The total UV radiation intensities from \(Xe (^{3}P_1)\) and \(Xe_2 (^{3}Σ_u^+, ^{1}Σ_u^+, O_u^+)\) are shown in Fig. 4. Here, \(R_{UV}\) is the rate of the radiative transition processes generating the UV radiation, which corresponds to the number of UV photons generated per unit time. It is therefore equivalent to the photon flux intensity from the PDP. The \(R_{UV}\) increases with \(P_{Xe}\). Whereas \(R_{UV}\) increases roughly linearly to \(V_s\) for 3.5%, \(R_{UV}\) saturates approximately at \(V_s \sim 350\ V\) for 10%–30%. This characteristic of the saturation is more remarkable for higher \(P_{Xe}\). Choi et al.\(^\text{15}\) experimentally observed the same trend in the UV intensity of the resonant line (147 nm) emissions, while the excimer emission intensity increased linearly by \(P_{Xe}\).

We define \(\eta_{dis}\) as the ratio of the total UV radiation energy \((W_{UV})\) per half cycle to \(W_{in}\) \((\eta_{dis} = W_{UV} / W_{in})\). The dependence of the discharge efficiency \(\eta_{dis}\) on \(V_s\) is shown in Fig. 5. The \(\eta_{dis}\) increases with \(P_{Xe}\), as is consistent with the experimental results.\(^\text{17,18}\) The \(\eta_{dis}\) exhibits a slight increase with \(V_s\) for 10% and 13.5%, and it peaks at \(V_s \sim 340\ V\) for 20% and 30%, while no significant change is seen for 3.5%.

The \(\eta_{dis}\) is parametrically given by the product of the electron heating efficiency \((\eta_{e})\) and UV efficiency \((\eta_{UV})\).\(^\text{3,4}\)

The former represents the percentage of \(W_{in}\) to be transferred to the energy of the electrons \((W_{e})\), and the latter represents...
the percentage of $W_e$ to be converted to the total UV radiation energy $W_{UV}$. Figure 6 shows the dependence of $\eta_e$ on $V_s$. The $\eta_e$ shows a step-wise increase for 10%–30%, instead of the constant value for 3.5%. The $\eta_e$ is as small as approximately 27% for $P_{Xe}=3.5\%$. This means that the ion heating loss, not the electron heating, of which the efficiency is equivalent to $1-\eta_e$, predominates here. The $\eta_e$ increases with $P_{Xe}$, 40%–50% of $W_{in}$ is converted to the electron energy for $P_{Xe}=30\%$. Increasing $P_{Xe}$ results in the enhancement in $\eta_e$ by 1.5–1.9. It is noted that high $\eta_e$ is attained for higher $P_{Xe}$ and $V_s$. The UV efficiency $\eta_{UV}$ is shown in Fig. 7. In the same manner as $\eta_e$, the $\eta_{UV}$ increases with $P_{Xe}$, $\eta_{UV}$ for 3.5\% does not show any dependence on $V_{sus}$, while $\eta_{UV}$ for 10\%–30\% shows a peak around 300 V. Thus, improvement is achieved both in $\eta_e$ and $\eta_{UV}$ by increasing $P_{Xe}$.

For all $P_{Xe}$, the ratios of the UV intensities from Xe(1$P_1$) and Xe$_2$(3$\Sigma^+_u$, 1$\Sigma^+_u$, $O_u^+$) relative to the total UV photon intensity show a minute change within 10\% in accordance with $V_s$. Figure 8 shows the relative ratio of the intensity from Xe(1$P_1$) and Xe$_2$(3$\Sigma^+_u$, 1$\Sigma^+_u$, $O_u^+$) as a function of $P_{Xe}$. Here, we take values averaged over $V_s$ for each $P_{Xe}$. The resonant radiation from Xe(1$P_1$) dominates for 3.5\%, while that from Xe$_2$(3$\Sigma^+_u$) becomes dominant over Xe(1$P_1$) for 10\%–30\%. Remarkably for 30\%, the intensity from Xe$_2$(3$\Sigma^+_u$) is even larger than that from Xe(1$P_1$). The ratio from Xe(1$P_1$) decreases with $P_{Xe}$. The ratios from two eximers Xe$_2$(3$\Sigma^+_u$, $O_u^+$) increase with $P_{Xe}$ and saturate at 20\% and 30\%, while the ratio from Xe$_2$(1$\Sigma^+_u$) increases linearly by $P_{Xe}$. When we take simply the sum of the ratios of Xe(1$P_1$) and Xe$_2$(1$\Sigma^+_u$), the sum is a constant value of approximately 50\% and notably independent from $P_{Xe}$, except for the value of 3.5\%.

### III. REACTION SCHEME

In Sec. III., we observed the increase of $\eta_{dis}$ with $P_{Xe}$. The parametric studies clarify that both $\eta_e$ and $\eta_{UV}$ increase with $P_{Xe}$, and $\eta_e$ shows a step-wise increase with $V_s$ while $\eta_{UV}$ shows a peak around $V_s=300$ V. Next, we will get insight into the reactions contributing to these behaviors of $\eta_e$ and $\eta_{UV}$. Here, we restrict our discussion on the reactions for $P_{Xe}=3.5\%$ and 30\%, in which two extreme conditions can be seen.

**A. $P_{Xe}=3.5\%$**

As can be seen in Fig. 8, the radiation from Xe(1$P_1$) and Xe$_2$(3$\Sigma^+_u$) dominates for 3.5\%. Figure 9 shows the reaction rates of the dominating production ($r_1$-$r_3$) and loss ($r_4$-$r_7$)
processes of Xe\(^{(3}\text{P}\,)}\) (for \(V_s = 240\text{ V}\)). Hereafter, all of the data presented are averaged spatially over the cross section and a half-discharge-cycle period. Most of Xe\(^{(3}\text{P}\,)}\) are produced from Xe** via collision with Xe. The electron impact excitation directly from Xe contributes less. The electron impact de-excitation of Xe\(^{(3}\text{P}\,)}\) dominates in the loss reactions. Approximately one-third of the produced Xe\(^{(3}\text{P}\,)}\) is converted into the UV radiation. The molecular state \(\text{Xe}_2\, (\Sigma_u^+)\) is produced by the three-body recombination with Xe and Xe\(^{(3}\text{P}\,)}\), \((r7)\), and converted via collisions with Ne or Xe into \(\text{Xe}_2\, (\Sigma_u^+)\), of which the state mainly decays via the UV radiation. Nevertheless, the process is minority in the loss processes.

It is well known that \(\text{Xe}_2\, (\Sigma_u^+)\) are produced by the three-body recombination with Xe and the metastable state \(\text{Xe}^{(3}\text{P}\,)}\). [Xe + Xe\(^{(3}\text{P}\,)}\) + Ne/\(\text{Xe} \rightarrow \text{Xe}_2\, (\Sigma_u^+)\) + Ne/\(\text{Xe}^\text{e}]. The three-body processes resulting in the radiative state \(\text{Xe}_2\, (\Sigma_u^+)\) generating UV radiation, but mostly they are excited back to Xe** via electron impact excitation. This backward process limits the \(\eta_{\text{dis}}\). The resonant radiation from Xe\(^{(3}\text{P}\,)}\), therefore, dominates, as shown in Fig. 8.

Figure 11 schematically summarizes the reactions related to the UV generation for 3.5%. The solid lines in Fig. 11 represent the electron impact processes and the broken lines represent the reaction with the neutral species, Ne and Xe. The UV radiation mainly consists of the spontaneous emissions from Xe\(^{(3}\text{P}\,)}\) and Xe\(^{(3}\Sigma_u^+)\). The direct excitations to both Xe\(^{(3}\text{P}\,)}\) and Xe\(^{(3}\Sigma_u^+)\) are not dominating production processes. Due to the relatively larger cross section in comparison with those for the direct excitation of Xe\(^{(3}\text{P}\,)}\) and Xe\(^{(3}\Sigma_u^+)\), the energetic electrons collide with Xe to excite them mainly to Xe**. The main loss processes of Xe** are the collisional de-excitation to Xe\(^{(3}\text{P}\,)}\) and Xe\(^{(3}\Sigma_u^+)\) with Ne and Xe (reaction rate \(-1\times10^{19}\text{ cm}^3\text{ s}^{-1}\)), the de-excitation to Xe\(^{(3}\text{P}\,)}\) and Xe\(^{(3}\Sigma_u^+)\) via spontaneous emission (\(-1\times10^{19}\text{ cm}^3\text{ s}^{-1}\)) and the ionization processes (\(~1\times10^{19}\text{ cm}^3\text{ s}^{-1}\)). Xe** is then converted to Xe\(^{(3}\text{P}\,)}\) and
Xe\(^{(3\,P_{\text{e}})}\) by the collisional de-excitation. Most of Xe\(^{(3\,P_{\text{e}})}\) are still destroyed by the electron impact excitation back to Xe\(^{**}\), as for \(P_{\text{Xe}}=3.5\%\). Xe\(^{**}\) is dominantly converted into Xe\(^{(3\,P_{\text{e}})}\) and Xe\(^{(3\,P_{\text{e}})}\) via collisions with Ne and Xe, in spite of the fact that electron impact de-excitation also contributes. Unfortunately, these states, being direct (resonant radiation) and indirect (excimer radiation) precursors of the UV radiation, are mostly excited back to Xe\(^{**}\) by the electron impact excitations. The spontaneous emission from Xe\(^{(3\,P_{\text{e}})}\) and the conversion processes of Xe\(^{(3\,P_{\text{e}})}\) to Xe\(^{(3\,P_{\text{e}})}\), which finally results in the UV excimer radiation, are minor reactions.

B. \(P_{\text{Xe}}=30\%\)

The spontaneous emission from Xe\(^{(3\,P_{\text{e}})}\) is no longer dominant in the UV radiation processes. The emission processes from the two molecular states Xe\(_2\)(\(3\,\Sigma_u^+\)) and Xe\(_2\)(\(3\,\Sigma_u^+\)) are the major UV radiation processes here. As for \(P_{\text{Xe}}=3.5\%\), we have confirmed that, also for \(P_{\text{Xe}}=30\%\), most of Xe\(_2\)(\(3\,\Sigma_u^+\)) is produced by the three-body recombinations of Xe\(^{(3\,P_{\text{e}})}\) with Ne via collisions with the third-body buffer gases (Ne and Xe). Thus, here, we study the production and loss processes of the precursor, Xe\(^{(3\,P_{\text{e}})}\), for Xe\(_2\)(\(3\,\Sigma_u^+\)). The reaction rates of the production and loss processes of Xe\(^{(3\,P_{\text{e}})}\) are shown in Fig. 12. The collisional de-excitation of Xe\(^{**}\) with Xe dominates in the production process. Although the electron impact excitation back to Xe\(^{**}\) is still the major loss process, but the conversion processes to Xe\(_2\)(\(3\,\Sigma_u^+\)) via collision with Ne and Xe [the reactions (m8) and (m9)] also contribute more in comparison with those for 3.5%. The produced Xe\(^{(3\,P_{\text{e}})}\) is mainly converted to Xe\(_2\)(\(3\,\Sigma_u^+\)) that eventually generates the excimer radiation.

As is seen in Fig. 9, for \(P_{\text{Xe}}=30\%\), the resonant radiation directly from Xe\(^{(3\,P_{\text{e}})}\) has a smaller contribution, but the excimer radiation from Xe\(_2\)(\(3\,\Sigma_u^+\)) rather dominates in the radiation processes involving Xe\(^{(3\,P_{\text{e}})}\). Here, Xe\(^{(3\,P_{\text{e}})}\) does not play a role as a UV radiator, but as the precursor to Xe\(_2\)(\(3\,\Sigma_u^+\)) becomes more dominant. Figure 13 shows the reaction rates of the production and loss processes of Xe\(^{(3\,P_{\text{e}})}\). Unlike for \(P_{\text{Xe}}=3.5\%\), most of Xe\(^{(3\,P_{\text{e}})}\) is produced via collisional de-excitation of Xe\(^{**}\) and the electron impact and radiative processes have relatively minute contributions. The electron impact de-excitation is the major loss process. The conversion process of Xe\(^{(3\,P_{\text{e}})}\) to Xe\(_2\)(\(O_{\text{u}}^+\)) via the three-body collisions with Ne and Xe exhibits a larger contribution in the loss process than the radiative decay process (r3). The reaction rate coefficient of the process involving Xe as the third collider is larger than that involving Ne. Hence, in the case when the Xe partial pressure is larger, the reaction rate of the reaction (r9) becomes larger.

Figure 14 schematically summarizes the reactions related to the UV generation for 30%. The solid lines in Fig. 14 represent the electron impact processes and the broken lines represent the reaction with the buffer gas species, Ne and Xe. The UV radiation mainly consists of the excimer radiation from Xe\(_2\)(\(3\,\Sigma_u^+\)) and Xe\(_2\)(\(3\,\Sigma_u^+\)). Exactly in the same way as for \(P_{\text{Xe}}=3.5\%\), energetic electrons excite Xe to Xe\(^{**}\). The direct excitations to Xe\(^{(3\,P_{\text{e}})}\) and Xe\(^{(3\,P_{\text{e}})}\) are not the dominant production processes. The main loss processes of Xe\(^{**}\) are the collisional de-excitation to Xe\(^{(3\,P_{\text{e}})}\) and Xe\(^{(3\,P_{\text{e}})}\) with Ne and Xe (reaction rate, \(~5.5\times10^{19}\text{ cm}^3\text{ s}^{-1}\)) the electron impact de-excitation to Xe\(_2\)(\(3\,P_{\text{e}}\)) and Xe\(_2\)(\(3\,P_{\text{e}}\)) (\(~6\times10^{18}\text{ cm}^3\text{ s}^{-1}\)), and the ionization reactions (\(~2.9\times10^{19}\text{ cm}^3\text{ s}^{-1}\)). The majority of Xe\(^{**}\) is then converted to Xe\(^{(3\,P_{\text{e}})}\) and Xe\(^{(3\,P_{\text{e}})}\) by the collisional de-excitation. Most of Xe\(^{(3\,P_{\text{e}})}\) are still destroyed by the electron impact excitation back to Xe\(^{**}\), as for \(P_{\text{Xe}}=3.5\%\). But some part is converted to the molecular state Xe\(_2\)(\(O_{\text{u}}^+\)) via three-body collisions. Xe\(_2\)(\(O_{\text{u}}^+\)) is de-excited to Xe\(_2\)(\(3\,\Sigma_u^+\)) via collisions with Ne and Xe, and then Xe\(_2\)(\(3\,\Sigma_u^+\)) eventually radiates the UV excimer emissions. Xe\(_2\)(\(3\,P_{\text{e}}\)) is generated from Xe\(^{**}\) by the collisional de-excitation with Ne and Xe, and also by the electron impact de-excitation. The backward process from Xe\(_2\)(\(3\,P_{\text{e}}\)) to Xe\(^{**}\) does not dominate here, but Xe\(_2\)(\(3\,\Sigma_u^+\)) is converted to Xe\(_2\)(\(3\,\Sigma_u^+\)) via three-body collisions with Xe and the buffer gases (Ne and Xe). Thus, the UV radiation in this condition is dominated by the molecular excimer radiation. It is noted.
that, for \( P_{Xe} = 30\% \), due to the high reaction rate of mainly three-body collisions involving Xe, the forward processes toward the radiative states dominates against the backward processes, like the electron impact excitation to \( \text{Xe}^{**} \). Therefore, \( \eta_{\text{UV}} \), the UV conversion efficiency, is higher than that for low \( P_{Xe} \).

IV. SUMMARY

We studied the reaction processes related to the UV production in a standard Xe–Ne ac-PDP for various Xe content. The two-dimensional, self-consistent, fluid model under the proposed boundary condition is employed to investigate the discharge mechanisms in PDPs with Xe–Ne gas mixtures.

First, the overall output performance of the PDP cell is studied. The UV intensity, equivalent to \( R_{\text{UV}} \), increases with \( P_{Xe} \). The \( R_{\text{UV}} \) saturates approximately at \( V_s \sim 350 \) V for 10%–30% and the saturation character is more remarkable for higher \( P_{Xe} \). The discharge efficiency, \( \eta_{\text{dis}} \), increases with \( P_{Xe} \). The \( \eta_{\text{dis}} \) peaks at \( V_s \sim 340 \) V for higher \( P_{Xe} \) (= 20% and 30%), while no significant change is seen for \( P_{Xe} = 3.5\% \) and the saturation character is more remarkable for \( P_{Xe} = 3.5\% \). The electron heating efficiency, \( \eta_e \), and the UV conversion efficiency, \( \eta_{\text{UV}} \), are both enhanced by increasing \( P_{Xe} \).

The relative ratio of the UV intensities from \( \text{Xe}(3P_1) \) and \( \text{Xe}_2(3\Sigma^+_u, \Sigma^+_u, \Omega^+_u) \) is calculated as a function of \( P_{Xe} \). The resonant radiation from \( \text{Xe}(3P_1) \) dominates for 3.5%, while that from \( \text{Xe}_2(3\Sigma^+_u) \) becomes dominant over \( \text{Xe}(3P_1) \) for 10%–30%. Remarkably for 30%, the intensity from \( \text{Xe}_2(3\Sigma^+_u) \) is even larger than that from \( \text{Xe}(3P_1) \). The ratio from \( \text{Xe}(3P_1) \) decreases with \( P_{Xe} \). The sum of the intensity ratios of \( \text{Xe}(3P_1) \) and \( \text{Xe}_2(3\Sigma^+_u) \) is a constant value of approximately 50% and notably independent of \( P_{Xe} \), except for the value of 3.5%.

For the partial Xe pressures of 3.5% and 30%, where we see the extreme contrast in the relative contribution of the resonant and excimer radiation in the total UV radiation processes, we study the reaction processes of the excited Xe states \( \{ \text{Xe}(3P_1) \} \) and \( \{ \text{Xe}(3P_2) \} \) which play important roles in the UV processes.

For \( P_{Xe} = 3.5\% \), the UV radiation mainly consists of the spontaneous emissions from \( \text{Xe}(3P_1) \) and \( \text{Xe}_2(3\Sigma^+_u) \). The direct excitations to both \( \text{Xe}(3P_1) \) and \( \text{Xe}(3P_2) \), the precursors to \( \text{Xe}_2(3\Sigma^+_u) \) are not dominant production processes. \( \text{Xe}(3P_1) \) and \( \text{Xe}(3P_2) \) are produced dominantly by collision de-excitation of \( \text{Xe}^{**} \) with Ne and Xe, in spite of the fact that electron impact de-excitation also contributes. Most of them are unfortunately excited back to \( \text{Xe}^{**} \) by the electron impact excitations. The spontaneous UV emission from \( \text{Xe}(3P_1) \) and the conversion processes of \( \text{Xe}(3P_2) \) to \( \text{Xe}_2(3\Sigma^+_u) \), which results finally in the UV excimer radiation, are minor reactions.

For \( P_{Xe} = 30\% \), the UV radiation mainly consists of the excimer radiation from \( \text{Xe}_2(3\Sigma^+_u) \) and \( \text{Xe}_2(3\Sigma^+_u) \). Here, \( \text{Xe}(3P_1) \) does not play a role as the UV radiator itself, but as the precursor to \( \text{Xe}_2(3\Sigma^+_u) \). The direct excitations to \( \text{Xe}(3P_1) \) and \( \text{Xe}(3P_2) \) are not the dominant production processes. Then, \( \text{Xe}^{**} \) is converted into \( \text{Xe}(3P_1) \) and \( \text{Xe}(3P_2) \) via collisions with Ne and Xe. Most of \( \text{Xe}(3P_1) \) is still destroyed by the electron impact excitation back to \( \text{Xe}^{**} \), as for \( P_{Xe} = 3.5\% \). \( \text{Xe}(3P_2) \) is generated from \( \text{Xe}^{**} \) by the collisional de-excitation with Ne and Xe, and also by the electron impact de-excitation. The backward process from \( \text{Xe}(3P_2) \) to \( \text{Xe}^{**} \) does not dominate here, but they are converted to \( \text{Xe}_2(3\Sigma^+_u) \) via three-body collisions with Xe and the buffer gases (Ne and Xe). Thus, the UV radiation in this condition is dominated by the molecular excimer radiation. It is remarked that, for \( P_{Xe} = 30\% \), due to the high reaction rate of mainly three-body collisions involving Xe, the forward processes toward the radiative states dominates against the backward processes, like the electron impact excitation to \( \text{Xe}^{**} \). Therefore, \( \eta_{\text{UV}} \), the UV conversion efficiency, is higher than that for low \( P_{Xe} \).

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