Paper

Diagnostics of Planar XeI* UV Exciplex Lamp Excited by Coplanar Surface Barrier Discharge

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ABSTRACT

In this contribution to the research, electrical, optical, as well as energetic properties of the coplanar surface barrier discharge (CSBD) operated with the Xe/I₂ and Kr / Xe / I₂ mixtures at pressures of $p(\text{Xe}) \leq 50$ kPa and $p(\text{Kr} / \text{Xe}) = 10 - 100$ kPa are presented. Varying the gas composition, pressure and pump pulse repetition rate makes it possible to control the discharge pattern and achieve a diffuse discharge or completely filamentary CSBD. The optimal UV output was obtained using Xe/I₂ = 20/0.04 kPa and Kr / Xe / I₂ = 46 / 4 / 0.04 kPa mixtures. The krypton admixture enhances the XeI(B – X) emission for about 15% in comparison with a binary Xe / I₂ mixture. The average radiation power and efficiency of 8 mW / cm² and 3% were measured at a frequency of 100 kHz.

KEYWORDS: planar exciplex lamp, emission spectra, xenon iodide, UV emission, radiant flux, efficiency

1. Introduction

Gas-discharge plasma on mixtures containing xenon and iodine vapours is considered to be an efficient source in the UVC (200–290 nm) range¹⁾²⁾. The strong XeI(B²Σ_{1/2} – X²Σ_{1/2}) emission at $\lambda_{\text{max}} = 253$ nm is an alternative source for the same wavelength as the low-pressure mercury lamp (253.7 nm). As presented in our previous studies concerning surface barrier discharge³⁾⁴⁾, krypton addition to the binary 'xenon/halogen' mixture resulted in UV output and discharge homogeneity enhancement. Excimer (exciplex) lamps with planar geometry also appear to be interesting for obtaining a homogeneous flat radiation flux. In this contribution we sought to determine whether that effect takes place for the coplanar surface barrier discharge (CSBD). The aim of this study is to investigate the generation of the XeI* emission by means of coplanar surface barrier discharge operated with the Xe / I₂ or Kr / Xe / I₂ mixtures.

2. Experimental

The CSBD electrode module was manufactured on a glass plate. Strip-like electrodes had a width of $d_2 = 2$ mm and the distance between strips was $d_1 = 1$ mm, the thickness of the glass layer above electrodes was $\Delta = 0.14$ mm (Figure 1). The electrode system was mounted inside a chamber of 1.5 l in volume. To excite a working mixture a generator of high voltage AC sinusoidal pulses was used; peak-to-peak voltage up to 10 kV, $f = 1 - 100$

kHz. The voltage U applied to the CSBD was measured using a high voltage probe (Tektronix P6015A). The waveforms of current I and charge Q were registered by means of a 50 Ω resistor or low-inductance $C_{\text{add}} = 8$ nF capacitor placed in series with the CSBD module and monitored by digital oscilloscope HP Infinium (500 MHz, 2 GS/s). The voltage across these elements (resistor and C_{add}) was monitored through an additional voltage probe (10×, Tektronix TPP1000) with impedance matching of the transmission line. The mean power dissipated in the discharge was determined using the Volt–Coulomb Lissajous dependences⁵⁾. The energy deposited into the gas-discharge plasma within one period was calculated as an area of the figure in charge–voltage coordinates. Multiplying the energy value by the pulse repetition frequency, the power supplied by the discharge was obtained.

Prior to the filling of gases the chamber was pumped down below 10 Pa. Iodine is a very hydrophilic substance and absorbed water leads to a shorter lifetime of the lamp due to formation of involatile species, mainly I₂O₅. Thus, iodine crystals were heated and dried by means of resublimation cycles. The working mixture of rare gases with iodine vapours was prepared directly inside the chamber. During the experiments, the iodine partial pressure was determined from the temperature of the coldest part of the chamber by interpolating the reference data⁶⁾ and at room temperature $T = 25^\circ\text{C}$ this corresponds

to $p(\text{I}_2) = 40 \text{ Pa}$.

The radiation emitted by the discharge was registered and analyzed in the spectral range of 200–900 nm. The spectra were recorded by the Jobin Yvon TRIAX 550 monochromator (grating 1200 grooves/mm, quartz optical fiber, the spectral resolution of about 50 pm) with the high-speed CCD Spectrum ONE detector. The spectra are presented in the original form without any gluing and filtering of noise. The second order of the spectrometer was not filtered. The system was calibrated in the range 200–400 nm by a deuterium lamp, and in the range 400–900 nm by a reference tungsten lamp. The radiation power of the CSBD in absolute units was measured by a UV power meter Lab Master Ultima equipped with two calibrated exchangeable sensor heads (for 250 – 400 nm and 400 – 1100 nm). As the power meter was not sensitive for wavelengths $\lambda < 250 \text{ nm}$ the power of emitted radiation in the range 200 – 250 nm has been estimated via spectral characteristics as a ratio of corresponding areas $k_1 = S_{(250-400 \text{ nm})} / S_{(200-400 \text{ nm})}$. The total radiant flux emitted into 2π solid angle was estimated using standard approach when the sensor head was placed at the distance ten times larger than geometric size of the emitting surface³⁾. The CSBD efficiency was determined as the ratio between the total UV radiant flux P_{out} and the input power P_{in} :

$$\eta = (P_{\text{out}} / P_{\text{in}}) \times 100\%.$$

Figure 1 Electrode system of CSBD

3. Results and discussion

Representative examples of measured voltage $U(t)$ and external total current $I(t)$ waveforms, as well as $U-Q$ loops for the $\text{Kr} / \text{Xe} / \text{I}_2 = 51 / 4 / 0.04 \text{ kPa}$ mixture are shown in Figure 2(a, b). In each half-cycle of the applied voltage U_0 , the current waveform consisted of a displacement current and sharp current peaks caused by the discharge, with characteristics depending on the operating frequency and applied voltage. The peak current did not exceed 55 mA and their duration was in the range 0.7–1 μs .

The plasma consisted of numerous H-shaped elementary discharges with brighter streamer-like filamentary plasma that bridges two clouds of diffuse plasma formed over the embedded electrodes. In the case of CSBD at $p(\text{Xe}) = 20 \text{ kPa}$ this research has revealed that

the discharge appearance is dependent on the operating frequency. At a frequency of 6 kHz the diffuse part of CSBD has a greater brightness than the filaments. However for the $f = 100 \text{ kHz}$ situation this is reversed: the filaments are much more intense than the diffuse plasma. From an engineering viewpoint, considering CSBD as a radiation source, it is possible to regulate the discharge pattern with the Xe / I_2 mixture by means of the operating frequency. Figure 3 illustrates the significant changes in the discharge appearance when krypton was added to the Xe / I_2 mixture. The discharge visually appears to be a homogeneous plasma layer with the more intensive parts over the electrodes. Brightness was also greater in comparison with the binary mixture.

(a)

(b)

Figure 2 Typical voltage and current waveforms (a) and charge-voltage Lissajous figure (b) of a CSBD operated in the $\text{Kr/Xe/I}_2 = 51 \text{ kPa} / 4 \text{ kPa} / 40 \text{ Pa}$ working mixture

Measurements of the UV-visible emission spectra of the CSBD revealed the strong $\text{XeI}^*(B-X)$ exciplex radiation at $\lambda_{\text{max}} = 253 \text{ nm}$. Weaker emissions of $\text{XeI}^*(B-A)$ ($\lambda_{\text{max}} = 320 \text{ nm}$), $\text{XeI}^*(C-A)$ ($\lambda_{\text{max}} = 265 \text{ nm}$), and $\text{I}_2^*(D-A')$ ($\lambda_{\text{max}} = 342 \text{ nm}$) were also observed. Atomic iodine is represented in the spectrum by the emission at $\lambda = 206.2 \text{ nm}$ ($^2P_{3/2} - ^2P_{1/2}$). The full width at half maximum (FWHM) of $\text{XeI}(B \rightarrow X)$ band decreased from 2.6 to 1.5 nm within the pressure range 5 - 100 kPa. Unlike the Xe / I_2 mixture, in the emission spectra of $\text{Kr} / \text{Xe} / \text{I}_2$ mixture it was

Figure 3 The comparison of different mixtures with specific parameters: Xe / I₂ = 10 kPa / 40 Pa, $f = 100$ kHz, $P_n = 15.1$ W (a) and Kr / Xe / I₂ = 55 kPa / 5 kPa / 40 Pa, $f = 6$ kHz, $P_n = 8.1$ W (b)

Figure 4 Emission spectra of the exciplex lamp with the Xe / I₂ = 25 / 0.04 kPa and Kr / Xe / I₂ = 46 / 4 / 0.04 kPa mixtures

Figure 5 Optimization of working pressure for the Xe / I₂ (1) and Kr / Xe / I₂ (2) mixtures at a frequency of 100 kHz

observed to exhibit greater intensity of I₂($\bar{D} \rightarrow A$) band in comparison with the XeI($B \rightarrow A$) radiation (Figure 4).

The output CSBD power was measured as a function of the xenon or 92%Kr + 8% Xe pressure for the Xe / I₂ or Kr / Xe / I₂ mixtures with a fixed I₂ pressure $p(I_2) = 40$ Pa. For a constant applied voltage, the UV output increased to a maximum value with gas pressure, and then falls when the gas pressure exceeds $p(Xe) > 25$ kPa with the Xe / I₂ mixture and $p(Kr/Xe) > 60$ kPa with the Kr / Xe / I₂ mixture (Figure 5). The average radiation power of 8 mW / cm² has been achieved with the Kr / Xe / I₂ = 46 / 4 / 0.04 kPa mixture at $f = 100$ kHz. The conversion efficiency of the CSBD varied with the electrical power, achieving maximum values of around 3%.

Figure 6 shows the XeI*($B-X$) and XeI*($B-A$) intensities as a function of operating frequency with the Xe / I₂ mixture. It rises with frequency without any signs of saturation in the given frequency range. The trend to the saturation in output radiation could be expected at further increasing of input power mainly due to overheating of the electrode system.

Figure 6 Brightness of the XeI($B-X$) and XeI($B-A$) bands as a function of frequency with the Xe/I₂ = 20/0.04 kPa mixture

The presented results show that an enhanced performance of the CSBD is derived from a discharge which is more diffuse than that achieved with Xe/I₂ mixtures. The spatial distribution and UV power of the CSBD can be improved significantly by utilizing a higher frequency and krypton-containing mixture.

It is known that in the mixtures of rare gases the effective energy transfer from lighter to heavier one takes place⁷. It was shown in⁸ that in discharge with the Kr/Xe mixture fast krypton component decreasing takes place due to the excitation and charge transfer processes:

Calculations⁹⁾ showed, that at low Xe percentage values $\delta < 10\%$ krypton direct excitation and ionization processes dominate with following charge and energy transfer. At the $\delta > 10\%$ xenon direct excitation and ionization play the main role. This is explanation why we used 8%Xe + 92%Kr mixture.

Calculations⁹⁾ have shown that increasing of discharge homogeneity can be explained by growth of electron diffusion coefficient from values about $3 \cdot 10^3 \text{ cm}^2\text{s}^{-1}$ in Xe / I₂ = 10 kPa / 40 Pa mixture to $6 \cdot 10^3 \text{ cm}^2\text{s}^{-1}$ in Kr / Xe / I₂ = 55 kPa / 5 kPa / 40 Pa one.

4. Summary

The optimal composition of Xe / I₂ = 20–30 / 0.04 kPa and Kr / Xe / I₂ = 40–60 / 4–5 / 0.04 kPa working mixtures from the point of view of maximum yield of $\text{XeI}^*(B-X)$ exciplex emission at $\lambda = 253 \text{ nm}$ and the effect of the excitation conditions on the CSBD have been established. As to the output radiation and discharge uniformity the addition of krypton enhances the XeI^* intensity at 253 nm about 15% in comparison with the Xe / I₂ mixture. It was possible to regulate the discharge pattern with the Xe / I₂ mixture by means of the operating frequency. UV radiation power density of $8 \text{ mW} / \text{cm}^2$ and the conversion efficiency from electrical input to maximum UV output of 3% were obtained with the Kr / Xe / I₂ = 46 / 4 / 0.04 kPa mixture at $f = 100 \text{ kHz}$.

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