Investigations of rare gas-iodine barrier discharge plasma

G.Zvereva\(^1\), S.Avdeev\(^2\), E.Sosnin\(^2\), M.Guivan\(^3,4\)

\(^1\) S.I.Vavilov State Optical Institute, St-Petersburg, 199034, Russia, E-mail: zvereva@soi.spb.ru
\(^2\) High Current Electronics Institute, Tomsk, 634055, Russia
\(^3\) Uzhgorod National University, Uzhgorod, 88000, Ukraine
\(^4\) Geothermal Anywhere, Dubravska cesta 2, Bratislava 84104, Slovakia

Abstract: Conditions for effective XeI\(^*\) formation in barrier discharges (volume and surface) in Xe with addition of I\(_2\) (P=0.3 Torr) were investigated. Radiation power of 14 mW/cm\(^2\) with efficiency up to 5.5% and 8 mW/cm\(^2\) with efficiency 3% were reached in the cases of pulse and sine excitation correspondingly. Harpoon reaction Xe\(^*\)+I\(_2\)→XeI\(^*\)+I was found to be the main channel of XeI\(^*\) excimer formation. Main pathways of electric energy loses were found to be ions heating. Addition of Kr to Xe-I\(_2\) mixture led to increasing of discharge homogeneity and appearance of new channels of excited xenon components formation. Investigations show, that decreasing of I\(_2\) concentration and optimization of pulse excitation can increase UV efficiency.

Keywords: barrier discharge, excimers, UV emission

1. Introduction

Plasma of xenon and iodine vapor mixtures is considered to be an efficient source in the VUV-UVC (λ=160-290 nm) area [1-3]. UV spectra of this region contain iodine atomic lines I\(^*\)(λ=160-200 nm, p\(^4\)s→p\(^5\)) and molecular band XeI\(^*\)(B\(^2\)\(\Sigma^+_1/2\)→X\(^2\)\(\Sigma^+_1/2\), λ~254 nm). XeI\(^*\) exciplex molecules emit radiation at the same spectral area as mercury atoms (254 nm) and XeI\(^*\) lamps can be considered as an alternative choice of low pressure mercury lamps. Iodine atomic lines are candidates for use in a long wavelength VUV light sources. Experimental and theoretical investigations give efficiency for 254 nm XeI\(^*\) band in the interval from 2% [4,5] up to 22% [2,3].

In the work experimental and theoretical investigations of Xe-I\(_2\) and Xe-Kr-I\(_2\) mixtures barrier discharge plasma, formation in it XeI\(^*\)(B\(^2\)\(\Sigma^+_1/2\)) exciplex molecules and excited iodine atoms I\(^*\)(p\(^4\)s) were carried out.

2. Formation of XeI\(^*\) UV exciplex radiation by coplanar surface barrier discharge

The discharge was generated on the surface dielectric barrier with embedded electrodes in planar design [6]. Strip-like electrodes had a width of 2 mm and the distance between strips was 1 mm, the thickness of the glass layer above electrodes was 0.14 mm. For discharge ignition sine voltage with amplitude up to 10 kV and frequency f=1-100 kHz was used. Input electrical power reached value 10 W.

Typical voltage and current waveforms of the coplanar surface discharge are shown in the Fig. 1. Typical discharge UV spectrum is presented in the Fig. 2. Addition of Kr to Xe/I\(_2\) mixture leads to significant increasing of plasma homogeneity (Fig. 3) and to 15% growth of UV intensity.
The computer simulation has shown that increasing of discharge homogeneity can be explained by growth of electron diffusion coefficient from values $3 \cdot 10^3 \text{ cm}^2\text{s}^{-1}$ in mixture $\text{XeI}_2$ (75/0.3 Torr) to $6 \cdot 10^3 \text{ cm}^2\text{s}^{-1}$ in $\text{Kr/Xe/I}_2$ (413/38/0.3 Torr) one (Fig.4).

Calculations show that main pathway of $\text{XeI}^*$ excimer formation is a harpoon reaction: $\text{Xe}^*+\text{I}_2 \rightarrow \text{XeI}^*+\text{I}$. Main channels of $\text{Xe}^*$ atom formation are direct excitation: $\text{Xe}+e \rightarrow \text{Xe}^*+e$ (dominates during current peak) and radiation decomposition of higher excited atoms $\text{Xe}^{**}$: $\text{Xe}^{**} \rightarrow \text{Xe}^*+\text{hv}$ (dominates in afterglow) (Fig.5). In $\text{Kr/Xe/I}_2$ mixture additional pathway of $\text{Xe}^{**}$ population appears due to energy transfer in reaction: $\text{Kr}^*+\text{Xe} \rightarrow \text{Xe}^{**}+\text{Kr}$ causes increasing of $\text{XeI}^*$ population.

The computer simulation has shown that increasing of discharge homogeneity can be explained by growth of electron diffusion coefficient from values $3 \cdot 10^3 \text{ cm}^2\text{s}^{-1}$ in mixture $\text{XeI}_2$ (75/0.3 Torr) to $6 \cdot 10^3 \text{ cm}^2\text{s}^{-1}$ in $\text{Kr/Xe/I}_2$ (413/38/0.3 Torr) one (Fig.4).

Calculations show that main pathway of $\text{XeI}^*$ excimer formation is a harpoon reaction: $\text{Xe}^*+\text{I}_2 \rightarrow \text{XeI}^*+\text{I}$. Main channels of $\text{Xe}^*$ atom formation are direct excitation: $\text{Xe}+e \rightarrow \text{Xe}^*+e$ (dominates during current peak) and radiation decomposition of higher excited atoms $\text{Xe}^{**}$: $\text{Xe}^{**} \rightarrow \text{Xe}^*+\text{hv}$ (dominates in afterglow) (Fig.5). In $\text{Kr/Xe/I}_2$ mixture additional pathway of $\text{Xe}^{**}$ population appears due to energy transfer in reaction: $\text{Kr}^*+\text{Xe} \rightarrow \text{Xe}^{**}+\text{Kr}$ causes increasing of $\text{XeI}^*$ population.
Experimental efficiency of UV radiation calculated as a ratio of radiation power to input electrical one was found to be equal to 3%. Necessary to note that with pulse excitation radiation efficiency can reach values up to 12% [7].

Experiments show that maximal UV emission intensity (254 nm) is reached at pressures 188 Torr for Xe-I$_2$ mixture and at 375 Torr for Kr/Xe/I$_2$ one, frequency increasing from 10 to 75 kHz leads to 10 times growth of UV power.

3. Formation of XeI$^*$ UV exciplex radiation by volume barrier discharge

In this part of work dielectric barrier discharge (DBD) with coaxial electrodes geometry ($D_1$=2.3, $D_2$= 4.3 cm, L=10 cm) in Xe-I$_2$ mixtures (P=60/0.3-120/0.3 Torr) was investigated. Excitation by pulses voltage with amplitude up to 4 kV and frequency 50 kHz was used.

Experimental UV power pressure dependencies, voltage and current time dependences and UV spectrum are presented in the Fig. 6-8. Necessary to note that only second peak of current outstrips voltage due to electric field of surface charges on dielectric barriers, first one is correlated with voltage front. The latter indicates that surface charge deposited in the previous pulse recombine during the period between pulses.

Grows of XeI$^*$ (254 nm) band intensity and falls of I$^*$ (206 nm, transition p$^3$s-p$^5$) one (Fig.6) could be explained by increasing of I$_2$ concentration. Maximum UV power of 2.3 W was reached at P=105 Torr with UV efficiency - 5.5%.

![Figure 6: I' and XeI' UV power as a function of gas pressure.](image)

![Figure 7: Voltage (1) and current (2) dependencies. Coaxial DBD Xe/I$_2$ (105/0.3 Torr).](image)

![Figure 8: Emission spectrum. Coaxial DBD Xe/I$_2$ (105/0.3 Torr).](image)
Calculations show that main channel of XeI* formation is a harpoon reaction
$\text{Xe}^* + \text{I}_2 \rightarrow \text{XeI}^* + \text{I}$, of losses – radiation
decomposition. Atoms $\text{I}^*$ mainly appear in
energy transfer reaction: $\text{Xe}^* + \text{I}_2 \rightarrow \text{Xe} + \text{I}^* + \text{I}$, disappear - due to quenching in reaction:
$\text{I}^* + \text{I}_2 \rightarrow \text{I}_2^* + \text{I}$. Main pathways of electric
energy loses are $\text{I}^-$, $\text{I}_2^+$ ions heating.

Conclusions

Experimental and theoretical study of Xe-
$\text{I}_2$ mixture (P=50/0.3-120/0.3 Torr) barrier
discharge show presence in UV spectra strong
iodine atomic line $\lambda=206$ nm and XeI* molecular $\lambda$~254 nm emissions. Addition to
Xe/I$_2$ mixture Kr leads to significant
increasing of plasma homogeneity and to
15% growth of UV intensity. Former can be
explain by growth of electron diffusion
coefficient, latter- by appearance of new
pathway of XeI* formation in energy transfer
reaction $\text{Kr}^* + \text{Xe} \rightarrow \text{Xe}^{**} + \text{Kr}$. UV efficiency
reaches value of 5.5% in the case of pulse
excitation and 3% in the case of sine one.
Decreasing of I$_2$ concentration and
optimization of pulse excitation (exclusion of
energy loses connected with surface discharge
recombination between pulses) can increase
UV efficiency.

References
and Kane D.M., Proceedings of LS-11,
Shanghai, China, 271 (2007).
and Brablec A., Appl. Phys. Lett. 81, 2716
(2002).
[7] Guivan M.M., St’ahel P., Brablec A.,
Janca J., Motomura H. and Jinno M,
Proceedings of LS-11, Shanghai, China, 547
(2007)