

## Excilamps as efficient UV–VUV light sources\*

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*Abstract:* Operating parameters of powerful UV and vacuum ultraviolet (VUV) excilamps with different discharge geometry excited by capacitive discharge, barrier discharge, glow discharge, and UV-preionized discharge were investigated. Intense radiation of  $\text{Ar}_2^*$ ,  $\text{Kr}_2^*$ ,  $\text{Xe}_2^*$ ,  $\text{ArF}^*$ ,  $\text{KrBr}^*$ ,  $\text{KrCl}^*$ ,  $\text{KrF}^*$ ,  $\text{XeI}^*$ ,  $\text{Cl}_2$ ,  $\text{XeBr}^*$ ,  $\text{XeCl}^*$ ,  $\text{XeF}^*$  molecules and  $\text{I}^*$  atoms was obtained in rare gas or in rare gas– $\text{F}_2$  ( $\text{Br}_2$ ,  $\text{CH}_3\text{Br}$ ,  $\text{Cl}_2$ ,  $\text{Br}_2$ ,  $\text{HCl}$ ,  $\text{I}_2$ ,  $\text{NF}_3$ ) mixtures.

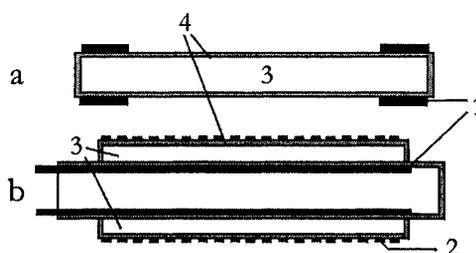
### INTRODUCTION

In recent decades, interest in design and development of new types of UV and VUV spontaneous radiation sources, in particular excilamps, has considerably grown [1–18]. The most efficient excilamps on transitions of rare gas dimers  $\text{R}_2^*$  and rare gas monohalides  $\text{RX}^*$  can find wide industrial application. Therefore, improving their output parameters is of great importance. In this paper, output parameters of excilamps with different geometry pumped by capacitive discharge, barrier discharges, glow discharges, and UV-preionized discharge are presented. The paper reviews some results obtained at the HCEI [8–18].

### EXPERIMENTAL SETUP

Designs of the cylindrical, coaxial (Fig. 1) and planar excilamps excited by barrier and capacitive discharge under study are described in [12,16,18].

Two types of pulsed generators were used for capacitive and barrier discharge formation. The first one produces sinusoidal voltage pulses with amplitude up to 10 kV and pulse repetition rate up to 100 kHz. In the second case, unipolar wave thyristor (or transistor), magnetic generators were used. The



**Fig. 1** Schematic diagram of electrodeless excilamps [capacitive (a) and barrier (b)]. 1 – solid electrodes; 2 – perforated electrodes; 3 – discharge volume; 4 – quartz envelopes.

\*Lecture presented at the 15<sup>th</sup> International Symposium on Plasma Chemistry, Orléans, France, 9–13 July 2001. Other presentations are presented in this issue, pp. 317–xxx.

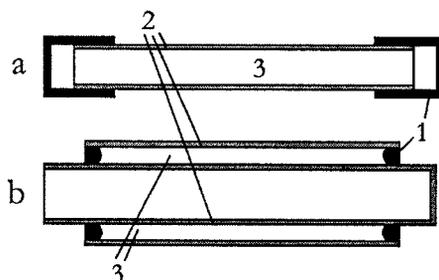
generators provided voltage pulses with duration from 20 ns to 10  $\mu$ s. A pulse repetition rate was up to 100 kHz.

The cylindrical and coaxial glow discharge excilamps (Fig. 2) were made from high-quality quartz tubes [10–12,14,15,17].

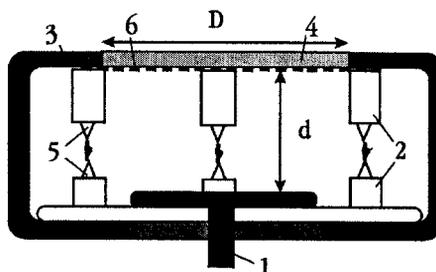
Diameter of the tubes was 10–60 mm and their length was up to 90 cm. The gap between the tubes in coaxial excilamp varied from 2.5 to 8 mm. Water-cooling of the inner tube or electrodes was used. The electrodes of glow discharge excilamps were coupled to dc power supply providing discharge current up to 1 A and voltage across the discharge gap up to 10 kV. AC power supply voltage was used in some experiments. The coaxial of barrier discharge and cylindrical of capacitive discharge excilamp (Fig. 2) were made from quartz tubes of high quality.

There were three types of pulsed excilamps in experiments with short pulse duration: such as a cylindrical glow discharge lamp, capacitive discharge lamp (electrodeless excilamp), and high pressure of volume discharge planar lamp with UV-preionization of discharge gap (Fig. 3) [8].

Average output and pulsed power were measured by photocathode FEK-22SPU. Excilamp spectra were recorded by monochromator MDR-23, equipped with photomultiplier FEU-100 or vacuum monochromator VMR-2 with 600 hatch/mm grating. The photomultiplier was connected to amplifier and registering system.



**Fig. 2** Schematic diagram of cylindrical (a) and coaxial (b) excilamps. Electrodes (1), quartz tubes (2), and discharge region (3) are designated.



**Fig. 3** Simplified diagram of UV-preionized self-sustained discharge excited lamp: 1 – solid electrode; 2 – peaking capacitors; 3 – causing; 4 – window; 5 – spark gaps for preionization; 6 – grid electrode; D – output window diameter; d – operation gap size.

## RESULTS

The operating parameters of powerful pulsed excilamps with different discharge geometry pumped by capacitive discharge, barrier discharge, glow discharge, and UV-preionized discharge were studied.

Intense radiation of  $\text{Ar}_2$ ,  $\text{Kr}_2$ ,  $\text{Xe}_2$ ,  $\text{ArF}^*$ ,  $\text{KrBr}^*$ ,  $\text{KrCl}^*$ ,  $\text{KrF}^*$ ,  $\text{XeI}^*$ ,  $\text{XeBr}^*$ ,  $\text{XeCl}^*$ ,  $\text{XeF}^*$ ,  $\text{Cl}_2^*$ ,  $\text{Br}_2^*$ ,  $\text{I}_2^*$ ,  $\text{IBr}^*$  molecules and  $\text{I}^*$  atoms was obtained in rare gas or in rare gas– $\text{Cl}_2$  ( $\text{Br}_2$ ,  $\text{CH}_3\text{Br}$ ,  $\text{F}_2$ ,  $\text{HCl}$ ,  $\text{I}_2$ ,  $\text{NF}_3$ ) mixtures [8–18]. The best results are as follows below.

An efficient low-pressure sealed-off cylindrical excilamp with capacitive discharge excitation was developed. Investigation was made of the characteristics of  $\text{XeCl}$  ( $\lambda \sim 308$  nm),  $\text{XeBr}$  ( $\lambda \sim 282$  nm),  $\text{KrCl}$  ( $\lambda \sim 222$  nm), and  $\text{XeI}$  ( $\lambda \sim 253$  nm) excilamps. High efficiency of exciplex molecules and simple design were obtained under capacitive HF discharge excitation. High UV radiation power and electrical power deposition to fluorescence conversion resulted in efficiencies of up to 15%. When the tube operates on  $\text{Xe–I}_2$  mixture in addition to B–X band of  $\text{XeI}^*$  molecules ( $\lambda \sim 253$  nm) band of  $\text{I}_2^*$  molecules at  $\lambda \sim 342$  nm and narrow (70 pm) resonant line of  $\text{I}^*$  at  $\lambda = 206.16$  nm were observed in glow discharge spectra. Output power up to 10 W and efficiency about 10% were obtained.

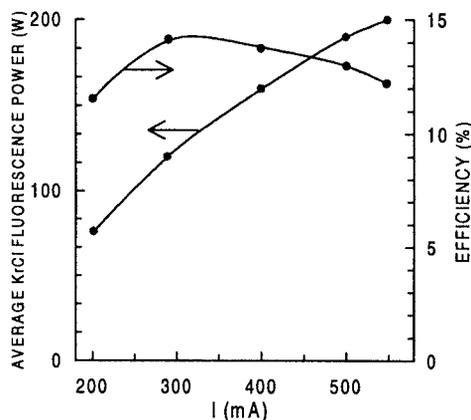
Gas mixture  $\text{He(Ne)–Xe(Kr,Ar)–Cl}_2$  ( $\text{HCl}$ ,  $\text{Br}_2$ ,  $\text{I}_2$ ,  $\text{F}_2$ ,  $\text{NF}_3$ ) at pressure of 0.1–1 atm was used in coaxial excilamps with barrier discharge excitation. UV output power and efficiency of 80 W and 10%, respectively, at  $\lambda \sim 222$  nm were obtained under excitation by pulses with frequency of 100 kHz.

The lifetime of gas mixture in  $\text{KrCl}^*$ ,  $\text{XeCl}^*$ ,  $\text{XeI}^*$  capacitive discharge and barrier discharge excilamps over 1000 h was demonstrated.

Coaxial excilamp pumped by a glow discharge with the gap of 8 mm was found to emit the highest average power. Output power at  $\lambda \sim 222$  nm up to 200 W (specific output power  $P_{sp} = 1$  W/cm<sup>3</sup>) was obtained (Fig. 4).

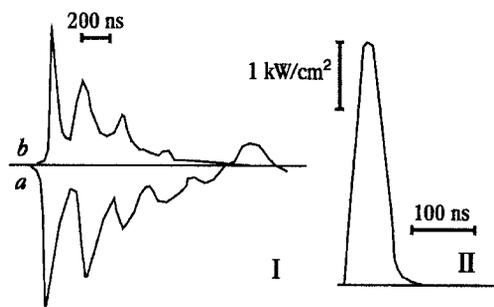
Efficiency with respect to input power as high as 14% was demonstrated. Similar results were obtained in  $\text{Xe–Cl}_2$  mixture at  $\lambda \sim 308$  nm. Output power of about 500 W was demonstrated when three excilamps operated in parallel. It was shown that the efficiency of luminescence of exciplex molecules  $\text{KrCl}^*$  up to 25% can be obtained in high-voltage glow discharge and positive column of glow discharge. Operation time of the excilamp is limited due to its overheating and exhaust of chlorine molecules. It is significant that enlargement of excilamp dimensions can substantially increase the operation time. Besides, upgrading of excilamp design, using stable to halogen action materials, cleaning of the original gas components, and improvement in water cooling show promise of substantial increase of the mixture lifetime.

Excilamps with high-pulsed power and short pulse have been developed. The effect of input electric power on the efficiency of the exciplex molecule luminescence was studied. The possibility of creation of capacitive discharge excilamps with short pulse duration was examined. In capacitive dis-



**Fig. 4** Output power and efficiency of  $\text{KrCl}$ -coaxial excilamp pumped by normal glow discharge vs. discharge current. The gap is 8.5 mm. Mixture  $\text{Kr:Cl}_2 = 10:1$ ,  $p = 6$  Torr.

charge cylindrical KrCl-excilamp, at  $\lambda \sim 222$  nm the radiation pulse power up to 2.5 kW was obtained. Powerful radiation pulses of 50 ns in duration were obtained at pulse repetition rate of 1 kHz. In cylindrical longitudinal excilamp with inner electrodes at Xe-I<sub>2</sub> mixture the total pulse power of 75 kW was measured. Under pumping by UV-preionized high-pressure volume discharge maximal pulsed radiation densities of 5 kW/cm<sup>2</sup> were obtained in mixtures Ne-Kr-HCl ( $\lambda \sim 222$  nm) and He-Kr-F<sub>2</sub> ( $\lambda \sim 250$  nm). Figure 5 shows the typical waveforms of current and lamp intensity.



**Fig. 5** Typical waveforms of current (a) and lamp intensity (b) in cases of electrodeless excilamp (I) and excilamp with additional UV-preionization of discharge gap (II). I – Mixture Kr:Cl<sub>2</sub> = 25:0.5 Torr. II – Mixture Ne:Kr:Cl<sub>2</sub> = 2 atm:45:2 Torr. Solid electrode diameter is equal to 40 mm; gap – 29 mm.  $U_g = 36$  kV,  $C_g = 4.2$  nF.

## CONCLUSION

Design and operating parameters of powerful UV and VUV excilamps with different discharge geometry pumped by glow discharge, high-pressure volume discharge with UV-preionization, capacitive discharge, barrier discharge were investigated. Intense radiation of Ar<sub>2</sub><sup>\*</sup>, Kr<sub>2</sub><sup>\*</sup>, Xe<sub>2</sub><sup>\*</sup>, ArF<sup>\*</sup>, KrBr<sup>\*</sup>, KrCl<sup>\*</sup>, KrF<sup>\*</sup>, XeI<sup>\*</sup>, Cl<sub>2</sub><sup>\*</sup>, XeBr<sup>\*</sup>, XeCl<sup>\*</sup>, and XeF<sup>\*</sup> molecules was obtained in rare gas or in rare gas-F<sub>2</sub> (CH<sub>3</sub>Br, Cl<sub>2</sub>, HCl, I<sub>2</sub>, NF<sub>3</sub>) mixtures [8–18]. Excilamps with high spatial uniformity of the output, narrow emission line, and long gas lifetime were developed. The lifetime of gas mixture in KrCl<sup>\*</sup>, XeCl<sup>\*</sup>, XeI<sup>\*</sup> capacitive and barrier discharge excilamps over 1000 h was demonstrated. It was shown that efficiency of luminescence of exciplex molecules KrCl<sup>\*</sup> of about 25 % can be obtained in high-voltage glow discharge and positive column of glow discharge. Output at  $\lambda \sim 222$  and 308 nm up to 200 W from single excilamp and 500 W from three excilamps operating in parallel was demonstrated. High efficiency (15 %) of exciplex molecules and simple design was obtained under capacitive HF discharge excitation. Under pumping by UV-preionized high-pressure volume discharge maximal pulsed radiation densities of 5 kW/cm<sup>2</sup> were obtained in mixtures Ne-Xe-HCl ( $\lambda \sim 308$  nm) and He-Kr-F<sub>2</sub> ( $\lambda \sim 250$  nm).

## ACKNOWLEDGMENT

We gratefully acknowledge the ISTC support Project #1270 in new works on development and application of UV and VUV excilamps.

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