Dielectric barrier discharge KrCl- and XeCl-excilamps radiation power control by pressure jump method

Eduard A. Sosnin*[a,b], Vladimir S. Kuznetsov[a,b], Maria V. Didenko[b], Victor A. Panarin [a]

[a]Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Akademichesky Ave., Tomsk, 634055, Russia;
[b]National Research Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia

ABSTRACT

The energy dissipation processes in dielectric barrier discharge KrCl- and XeCl-excilamps at various voltage, frequencies and pulse duration are revealed by a pressure jump method. It is offered and tested a way of radiation power calculation in conditions of non-uniform filling of device bulb by discharge plasma. The previous data (Pikulev A.A., Sosnin E.A., 2010-2013) are confirmed. The regularity was formulated: conditions of maximal ultraviolet radiation power corresponds to conditions of maximal heat release in plasma.

Keywords: dielectric barrier discharge, isochoric process, heat release, radiant power, excilamp.

1. INTRODUCTION

Barrier discharge devices are now widely used in research and industry. In particular, barrier discharge is most often used for obtaining ultraviolet (UV) and vacuum ultraviolet (VUV) radiation of exciplex and excimer molecules and relevant devices are called excilamps[1–3].

Implementation of excilamps implies conducting research aimed at optimizing their operation modes under long-term service conditions, such as gas mixture composition, excitation conditions, temperature of working gas and excilamp bulb, choice of cooling modes (air or water), and above all else simplification of their manufacturing procedure. In this case express control methods of excilamp radiant power are needed which don't use expensive and sophisticated equipment (photodetectors, ocsillographs and spectrophotometers).

As it was shown in papers[2,4–10], the choice of barrier discharge excilamp operation mode can be made by recording thermodynamic parameters of the system. In order to do this gas mixture is viewed as a thermodynamic system whose temperature increase (when switching on and during operation) takes place at constant volume (isochoric process).

We used this method in the current work to determine the influence of excitation pulse duration on the energy balance in XeCl- and KrCl- coaxial barrier discharge excilamps excited from the tunable power source.

2. EXPERIMENTAL EQUIPMENT AND RESEARCH TECHNIQUES

The layout of the experimental setup is shown in Figure 1. The bulb of barrier discharge excilamps had a coaxial structure (Figure 1, Table 1) and was made up of tubes *1* and *2* of TKg quartz or KV-2 quartz (Technoquartz, LLC). External radiuses of tubes amounted to 39.4 and 23.6 cm respectively. The discharge took place when voltage pulses were supplied to electrodes from source *6*, and radiation from the gas discharge volume was output through the perforated electrode. The length of the bulb working zone in which the discharge occurred was 7.9 cm. Therefore, the full and the discharge volume of the bulb amounted to 116.4 and 136 cm^3.

Power source *6* was responsible for adjusting voltage amplitude (from 1 to 8 kV), pulse repetition rate (from 10 to 90 kHz) and pulse duration (from 0.5 ns to 2 μs).

The working mixtures were prepared in the separate exhaust unit. The following mixtures were studied: Xe-Cl_2 with the ratios (200-50)/1 with general pressure values up to 300 Torr; and Kr-Cl_2 with the ratios (400-50)/1 with general pressure values up to 300 Torr.

International Conference on Atomic and Molecular Pulsed Lasers XII, edited by Victor F. Tarasenko, Andrey M. Kabanov, Proc. of SPIE Vol. 9810, 98101U · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2224940

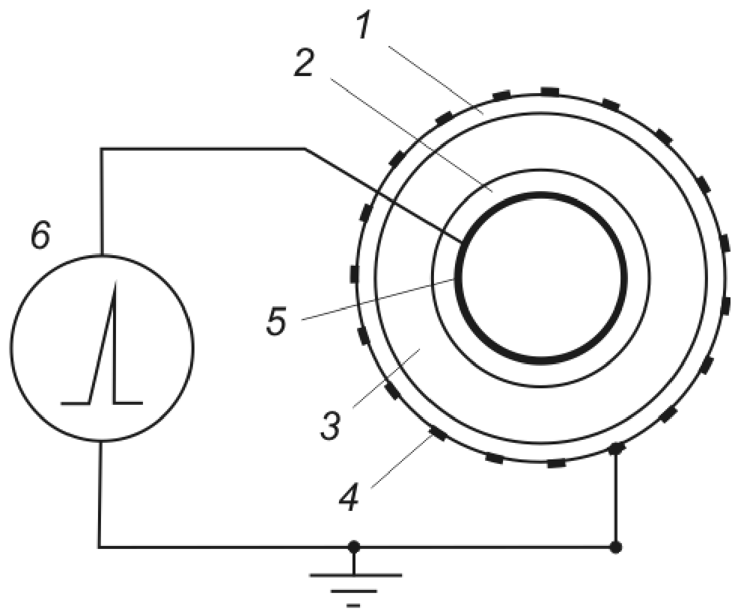

Figure 1. Design of coaxial barrier discharge excilamp (the bulb of the lamp is given in the radial section): (*1*,*2*) external and internal quartz tubes of the bulb, (*3*) discharge interval, (*4*) external perforated electrode, (*5*) internal reflecting electrode, (*6*) pulse power source.

The standard time code of the pressure value in the excilamp bulb after discharge ignition is shown in Figure 2. It is seen that after switching on (t_0), pressure rises fast from the initial value p_0 to the value $p_0 + \Delta p_1$ (where Δp_1 – is a so called amplitude of the *quick* component of pressure jump. The characteristic time for this process is ~100 ms depending on the composition, mixture pressure and excitation power. At time t_1, slow linear pressure growth with the value Δp_2 at big time values takes place. The transfer of the energy scattered in the volume of the bulb to the walls of the device corresponds to it. After switching off the lamp (at time t_2), the rapid pressure decrease by the value Δp_1 (~100 ms) to the value $p_0 + \Delta p_2$ occurs where Δp_2 is the amplitude of the slow component of pressure jump. Then slow pressure drop occurs to the initial value p_0 corresponding to bulb cooling.

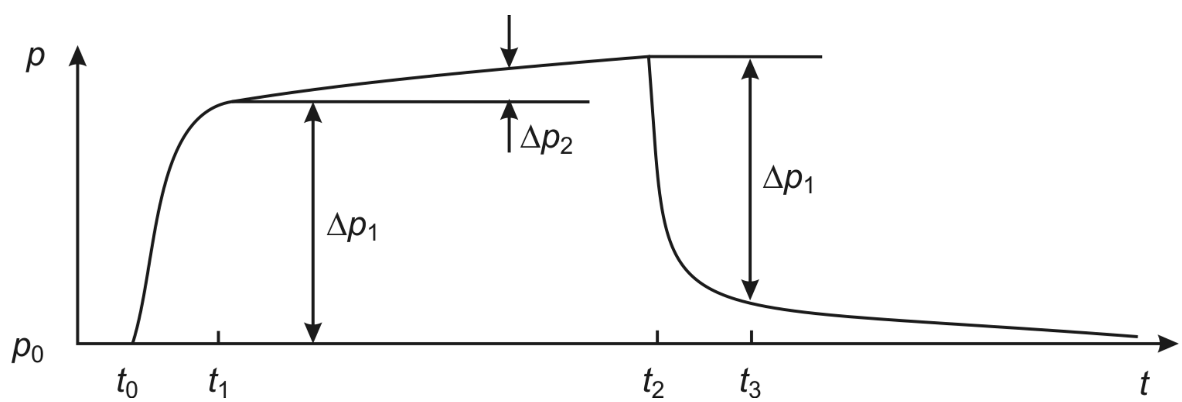

Figure 2. Standard time dependence of the pressure value in the excilamp (details in the text)

In order to record values p_0 and Δp_1 in the bulb DMP 330L pressure sensor (BD Sensors RUS, LLC, Moscow) was used whose measurement error within the pressure range up to 1 atmosphere does not exceed ± 0.5%.

In order to record the value of radiation power on the bulb surface value of radiant exitance E was recorded by HAMAMATSU H8025-222 photodetector with the maximum spectral sensitivity $\chi(\lambda)$ on the wavelength λ = 222 nm.

Usually, total average radiation power of the excilamp is calculated in the following way

$$P_{UV}^{*} = E \cdot S \cdot \frac{\int \chi(\lambda) \cdot I(\lambda) \cdot d\lambda}{\int I(\lambda) \cdot d\lambda}, \quad (1)$$

where S is total area of the bulb emitting surface, cm²; $I(\lambda)$ – radiation spectrum within the photodetector sensitivity range. This is true for the cases when the working zone of the lamp is uniformly filled with the discharge. However, it is known that with the pressure increasing the type of discharge changes from volumetric to the combination of microdischarges and then to thin filaments and even sparks. At the last two stages the filling of the bulb with microdischarges goes down. Consequently, formula (1) should contain multiplier $k = V/V_{dis}$ (where V, V_{dis} – discharge volume and real volume occupied by the discharge respectively) taking into account the degree of filling the bulb with microdischarges and/or sparks. Value E should be measured in that part of the bulb which is uniformly filled with the discharge. How can we define k?

In accordance with [5,7,8], thermal power emitted in the plasma of the coaxial BD excilamp, amounts to:

$$W \approx \frac{12 \cdot \xi \cdot \Delta p_1 \cdot V \cdot T_0}{p_0 \cdot d^2} \approx \frac{\Delta p_1}{p_0}, \quad (2)$$

where ξ is thermal conductivity coefficient, W/m·K; T_0 – gas temperature in the bulb (before discharge ignition); d – length of the discharge interval, m.

On the other hand, it is shown in [6] that value k is proportionate to W, namely

$$k \sim \Delta p_1/p_0. \quad (3)$$

Then radiation power adjusted according to the degree of filling the bulb with discharge amounts to

$$P_{UV} = P_{UV}^{*} \cdot k_{norm}, \quad (4)$$

where k_{norm} is a standardized filling coefficient (3).

3. RESULTS AND DISCUSSION

The examples obtained as a result of measurements and calculations (1)-(4) of values $\Delta p_1/p_0$ and $P_{UV,}$ as well as dependencies are given in Figure 3.

It is seen that for $Xe\text{-}Cl_2$ and $Kr\text{-}Cl_2$ mixtures these values have an extrema at pressure values p_{ext} about 60 and 100 Torrs respectively. How can it be explained? From the thermodynamic point of view, when $p \sim p_{ext}$, the amount and intensity of radiation of volumetric thermal sources in the discharge bulb is maximal. When $p < p_{ext}$, they also fill the whole volume but intensity of heat emission is lower as the number of gas particles for heating is smaller. When $p < p_{ext,,}$ the discharge finally switches from the volumetric burning type to the microdischarge and filament which also reduces thermal emission in the plasma.

Similar dependencies were observed at other values of τ, f and U_{max}.

The relative proportionality of values $\Delta p_1/p_0$ and P_{UV} is quite noticeable which was mentioned previously while studying other operation modes of excilamps, including those on other working molecules and having another design of the bulb [2,4–10]. Thus, having all this obtained data in view the following regularity can be formulated:

In barrier discharge excilamps, the conditions for achieving maximum values of average power and intensity of radiation meet the conditions of maximum heat emission in the discharge plasma.

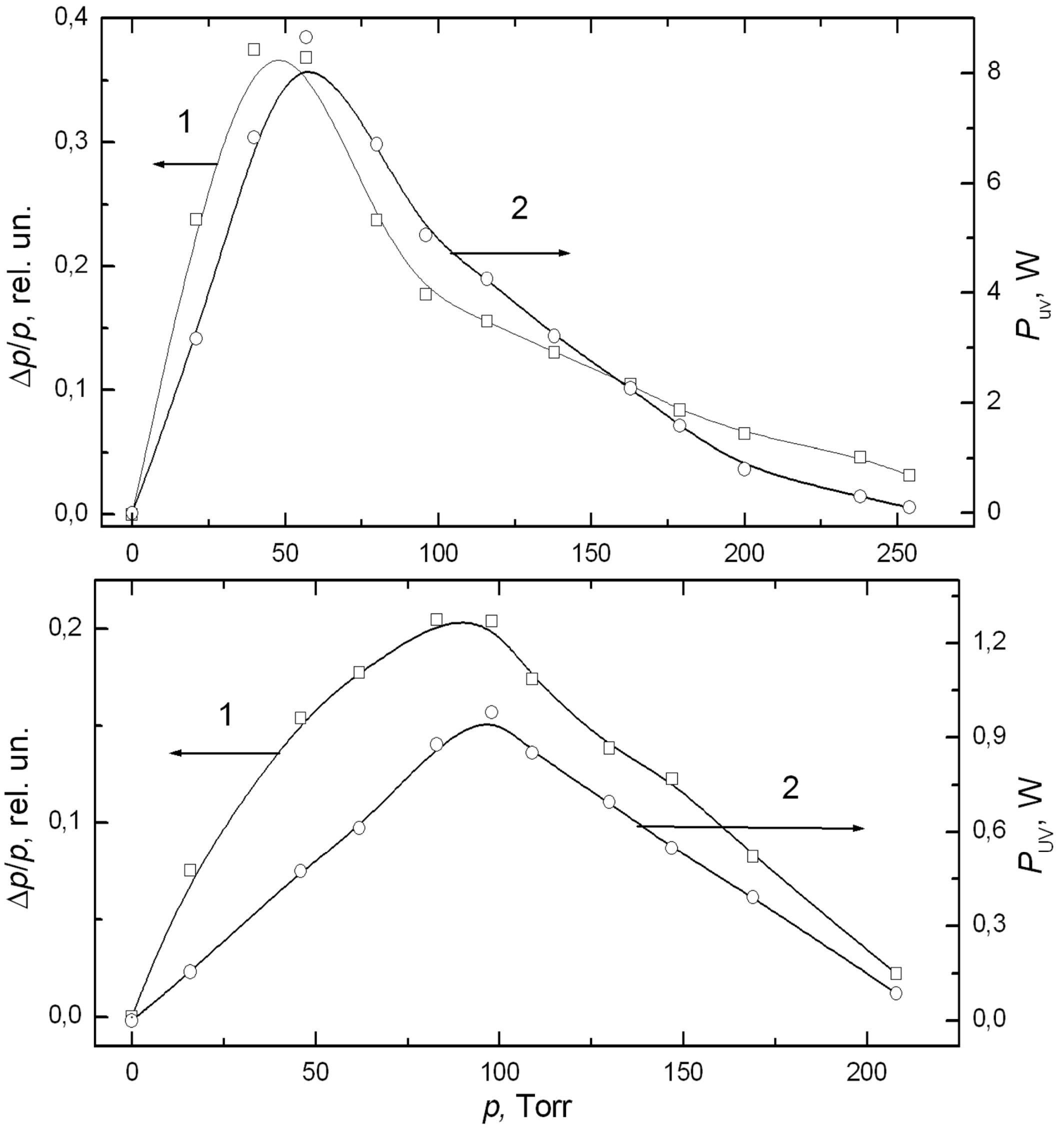

Figure 3. Values $\Delta p_1/p_0$ (1) and average power of ultraviolet radiation (2) for XeCl (at the top) and KrCl (at the bottom) of BD excilamps. Power supply to XeCl-excilamps is provided from the power supply unit with the pulse duration τ = 0.6 ms, frequency f = 40 kHz, maximum voltage amplitude U_{max} = 2.42 kV; to KrCl-excilamp -from the power supply unit with τ = 1.4 ms, f = 46 kHz, U_{max} = 2.83 kV

Therefore, the results of the performed measurements are in compliance with the previous studies and allow to conclude that when a barrier discharge excilamp is represented as a thermal machine, the maximum *yield*, i.e. the maximum output of UV radiation is attained at maximum values of heat emission in plasma. Maximum filling of the device bulb [6,11] with plasma also meets these conditions. From the practical standpoint, it means that control over radiation power of BD excilamps (irrespective of the values of τ, f and U_{max}, working mixture composition and device design) can be exercised by recording not optical but thermodynamic values. This simplifies the procedure of barrier discharge excilamps manufacturing and is important for their implementation.

4. CONCLUSION

It is offered and tested a way of radiation power calculation in conditions of non-uniform filling of device bulb by discharge plasma. The previous data (Pikulev A.A., Sosnin E.A., 2010-2013) are confirmed. It can be formulate the following conclusion based on pressure jump method: In barrier discharge excilamps, the conditions for achieving maximum values of average power and intensity of radiation meet the conditions of maximum heat emission in the discharge plasma.

The work has been fulfilled under partial financial support of the Russian Foundation for Fundamental Research (project 12-08-00020-a) and within the framework of the state assignment of the Institute of High Current Electronics of the Siberian Branch of the Russian Academy of Sciences; the subject # is 13.1.3. The authors are grateful to D.S. Pechenitsyn for preparing the power supply source.

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