Barrier discharge planar excilamps

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The comparison of power and spectral characteristics of barrier discharge planar excilamp in binary mixes Kr–Cl_2, Xe–Cl_2, Xe–Br_2, Ar–Cl_2, Kr–Br_2 is carried out. In a row of XeCl-, XeBr-, KrCl-, KrBr-, Cl_2-excilamps, radiant power densities of 39, 30, 19.3, 11.4, and 9.9 mW/cm^2 have been obtained. The comparison with coaxial barrier discharge excilamps in optimal (from the point of view of radiant power and uniformity of flask filling with microdischarges) conditions has revealed a low efficiency of planar excilamps. In a planar design the distribution of a light flow was nearly uniform over the output window.

The sources of spontaneous ultraviolet (UV) radiation and vacuum ultraviolet (VUV) radiation of bound-free transitions of excimer (R_2^*, X_2^*) or exciplex (RX*) molecules, where R is an inert gas (Ar, Kr, Xe), and X is a halogen (F, Br, Cl, I), have been thoroughly studied during the last decades.[1–4] The spectrum of excilamps is usually concentrated in one comparatively narrow and intensive emission band. The half-width of the band ranges from 2 to 15 nm for RX* molecules, reaching ~30 nm for R_2^* molecules. Apart from the radiation of intensive bands $B \to X$, the plasma spectrum of RX* exciplex molecules can include bands of other transitions: $D \to X$, $C \to A$, or $D \to A$ of the same molecule. Under high pressures (> 100 Torr) their intensity is negligibly small.[1,4–6]

Coaxial excilamps are commonly used for excitation of a barrier discharge (BD).[2,3,5–10] Planar excilamps on halides of inert gases are still poorly studied.

Spectral research of an excilamp with 4.7 cm^2 window area in Kr–Br_2, Kr–I_2 mixes is presented in Ref. 11. Under conditions, when $B \to X$ band of KrBr*-molecule is the most intensive, a 3 mW average power was obtained at a pressure of 285 torr. The spectral and power characteristics of an excilamp with 10 cm^2 window area in He–Kr–Cl_2 mixes were investigated in detail.[12] The efficiency of 15% and radiation power density of 100 mW/cm^2 were obtained. However, attempts to replicate these characteristics in further investigations have not been successful.

The spectral and power characteristics of XeCl* and KrCl* molecular radiation in surface barrier discharge at a 100 cm^2 window area and in Kr–Xe–Cl_2 mixes were thoroughly studied.[13] The efficiency of 8% and radiation power density of 6 mW/cm^2 were obtained.

Any published data on comparisons of the conditions of spontaneous radiation formation in barrier discharge under similar excitation conditions are unknown to us. This paper presents the results of a systematic study of these conditions.

The experiments were conducted using the setup presented in Fig. 1.

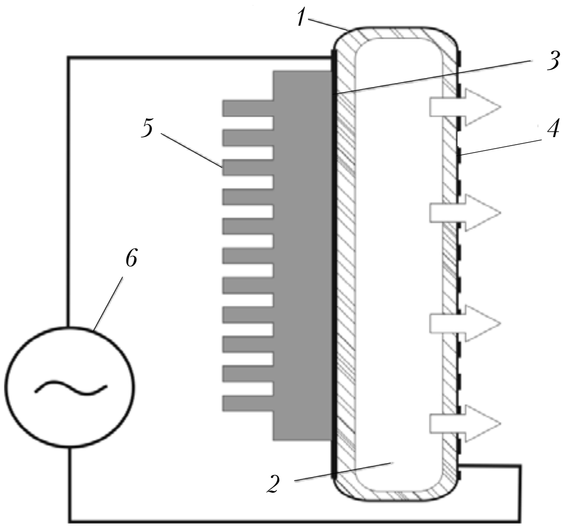

Fig. 1. Setup construction: planar flask (*1*); gas-discharge volume (*2*); solid reflecting electrode (*3*); perforated electrode (*4*); radiator (*5*); pulse energy source (*6*). The arrows indicate the direction of radiation output.

The flask *1*, made of quartz plates with more than 90% transmittance at $\lambda = 200$ nm, has a gas-discharge gap d of 8 mm in diameter. Perforated electrode *4* is made of metal net with a 72% transmittance. The output window diameter is 5.8 cm and its area is 26.4 cm^2. Solid reflecting electrode *3* is made of aluminum-magnesium foil. The gas medium in the gap *2* between quartz plates was excited with the voltage pulse generator. The pulses have the meander shape, amplitude of 5 kV, and a duration of 1.5 ms. Pulse repetition rate f is 117 kHz.

In the experiments, the partial pressure, as well as the proportion between halogen (Br_2, Cl_2) and inertial gas (Ar, Kr, Xe) varied. Besides, the radiation power and the power, input in discharge, were measured, as well as radiation spectra were recorded.

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The total pressure of mixes in our experiments did not exceed 400 torr. To provide the excilamp stable operation, the copper radiator *5* was attached to the electrode *3*, which cooled the emitter. During our experiments, the output window temperature did not exceed 75°C.

The lamp radiation power was measured with the HAMAMATSU H8025-222 photodetector, which has the maximum of spectral sensitivity at $\lambda = 222$ nm. The discharge radiation spectrum was recorded by the StellarNet EPP2000-C25 (StellarNet Inc.) spectrometer based on Sony ILX511 multichannel CCD-bar (a working range 200–850 nm, spectral half-width of its apparatus function does not exceed 1.5 nm). The improved spectrum was recorded with the complex consisting of two HR4000 (Ocean Optics B.V.) spectrometers covering a range 200–350 nm, and a diffraction grating with 2400 rulings/mm. Input power was determined by oscillograms of voltage and current pulses. The oscillograms from current shunt and voltage divider were recorded by TDS 224 (Tektronics Inc.) oscilloscope.

The formation of exciplex molecules in the pressure range under study ($p < 200$ torr), i.e., at moderate pressures, proceeds in the following reactions [Refs. 15–18]:

$$R + e \rightarrow R^* + e, \quad (1)$$

$$R^* + X_2 \rightarrow RX^* + X, \quad (2)$$

$$R_2^* + X_2 \rightarrow RX^* + R + X, \quad (3)$$

$$R + X_2^{**} \rightarrow RX^* + X, \quad (4)$$

and the formation of Cl_2^* and Br_2^* are in reactions [Refs. 16 and 17]:

$$X^* + X_2 \rightarrow X_2^* + X, \quad (5)$$

$$X(X_2) + e \rightarrow X^*(X_2^*) + e, \quad (6)$$

$$R^*(R_2^*) + X_2(X) \rightarrow R + X_2^*(X^*), \quad (7)$$

$$R^*(R_2^*) + X \rightarrow R(2R) + X^*, \quad (8)$$

$$X^+ + X^- \rightarrow X_2^*. \quad (9)$$

Therefore, radiation spectra contain not only the bands of exciplex molecules XeCl*, XeBr*, KrCl* and KrBr*, but also the bands of Cl_2^* and Br_2^* molecules.

Radiation spectra in Kr–Cl_2, Xe–Cl_2, and Xe–Br_2 mixes in optimal conditions (by average radiant power and the uniformity of flask filling with microdischarges) and at a total pressure of 120 torr consisted of intensive bands $B \rightarrow X$ of KrCl* (222 nm), XeCl* (308 nm), and XeBr* (283 nm) exciplex molecules with half-widths $\Delta\lambda_{1/2}$ of 1.6; 2.5 and 1.8 nm, respectively. The band intensity of other transitions $D \rightarrow X$, $C \rightarrow A$, $D \rightarrow A$ was low and decreased at the pressure increase.

At excitation of Ar–Cl_2 mix at ~ 300 torr pressure, the radiation spectrum in a range 200–850 nm had one intensive band $D' \rightarrow A'$ of Cl_2^* molecule with $\Delta\lambda_{1/2} \sim 5$ nm.

Radiation spectrum in Kr–Br_2 mix consisted of intensive bands $B \rightarrow X$ of KrBr* molecule with maximum at $\lambda = 207$ nm and the sum of weak bands $C \rightarrow A$ (222 nm), $D \rightarrow A$ (228 nm), and $D' \rightarrow A'$ (291 nm) of Br_2^* molecule. The decrease of bromine share in a series of mixes of Kr/Br_2 = = 100/1 → 400/1 has led to a relatively weak increase of Br_2^* molecule intensity and the increase of contribution to radiation of Br_2^* bands. At fixed Kr/Br_2 ratio in the mix, the increase of mixture pressure always led to increasing contribution to radiation of KrBr* molecule bands; and the contribution of $D' \rightarrow A'$ band of Br_2^* molecule practically did not change. In optimal conditions at about 190 torr pressure, radiation spectra consisted of $B \rightarrow X$ intensive bands of KrCl* (222 nm) and XeCl* (308 nm) exciplex molecules with $\Delta\lambda_{1/2} = 1.6$ and 2.8 nm.

The barrier discharge at low pressures had the form of volume glow in all cases except for the Ar–Cl_2 mix. With the increase of pressure, individual microdischarges appeared against the background of volume glow. Their intensity increased while the intensity of the background decreased. At the beginning, the number of discharges was great, however, during transition to high pressures ($p > 120$ torr) their number reduced up to one bright microdischarge.

Typical dependences of radiation power and efficiency on inertial gas pressure in Xe–Br_2 mix are shown in Fig. 2. Maximal values were obtained at $p \sim 120$ torr. The conditions in the discharge are optimal in this case.

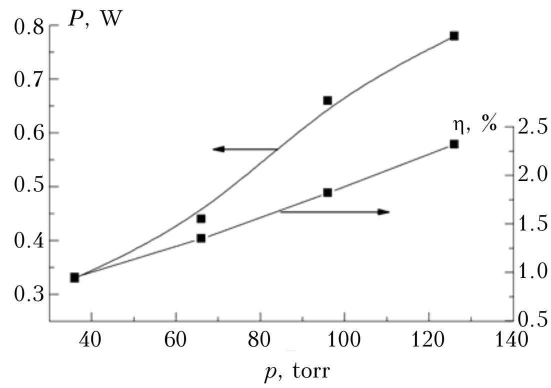

Fig. 2. The dependence of excilamp radiation average power and efficiency in Xe–Br_2 = 400–1 gas mix on the pressure of inertial gas.

In Ar–Cl_2 mix the discharge uniformly filled the flask throughout pressure range (up to 400 torr).

The best (in the above sense) results obtained in optimal conditions are illustrated in Table.

As is seen from the Table, excilamp radiation power and efficiency decrease in the row XeCl > XeBr > KrCl > KrBr > Cl_2. Let us compare these results with those obtained at the excitation of the same media in BD conditions in excilamp of coaxial construction. For example, in optimal conditions in KrBr-, Cl_2-, KrCl- BD excilamps of coaxial type, radiation power density was ~12,5; 2,4; 28 mW/cm^2 with a radiation efficiency of 1.9; 0.45; 5.2%, respectively.[14] Relatively low values of planar BD excilamps radiation efficiency, probably, are caused by mismatching with high-voltage pulse generator. Besides, thermal mode of excilamp operation changed: one of the walls was not cooled while the flask surface of coaxial BD excilamps is always cooled either by air flow or by water.[9] Consequently, the thermal mode of planar excilamps is to be studied.

Table. The characteristics of barrier discharge planar excilamps

Excilamp	The ratio of gas mixture components R / X_2	Total pressure of the mixture, torr	Radiation power density, mW/cm^2	Efficiency, %
XeBr	400/1	126	30	2.3
KrBr	400/1	195	11.4	0.9
XeCl	400/1	144	39	3
KrCl	400/1	171	19.3	1.5
Cl_2	400/1	310	9.9	0.75

Radiation spatial distribution over the output window of planar excilamps was inhomogeneous. However, if the irradiated object did not closely faced the lamp plane, but was located at a distance of 5 cm from it, then the irradiation close to homogenous can be gained in a spot of 5 cm in diameter with ~25% intensity difference in the center and at the edges. It is impossible to get such spatial distribution using a coaxial lamp, therefore, the planar lamps can be used in cases when it is necessary to get the homogenous irradiation.

Thus, systematic investigations of excilamp spectral and energy characteristics were conducted with several working molecules in the pressure range of halogen (Br_2, Cl_2) and inertial gas (Ar, Kr, Xe) mixes at pressures from dozens to 200 torr. The comparison with coaxial BD excilamps in optimal (by average radiation power and the homogeneity of flask filling with microdischarges) conditions revealed a lower efficiency of planar excilamps. However, the advantage of planar excilamp BD is a possibility to get the homogenous distribution of light flow over the window.

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References

1. B. Gellert and U. Kogelschatz, Appl. Phys. B **52**, 14–21 (1991).
2. M.I. Lomaev, E.A. Sosnin, and V.F. Tarasenko, *Low-temperature Plasma Encyclopedia* (PHYSMATLIT, Moscow, 2005), Vol. XI-4, pp. 522–546.
3. E.A. Sosnin, T. Oppenländer, and V.F. Tarasenko, J. Photochem. Photobiol. C: Reviews **7**, 145–163 (2006).
4. I.W. Boyd, J.-Y. Zhang, and U. Kogelschatz, in: A. Peled, ed., *Photo-Excited Processes, Diagnostics and Applications* (Kluwer Academic Publishers, The Netherlands, 2003), 161–199 pp.
5. E.A. Sosnin, M.V. Erofeev, A.A. Lisenko, M.I. Lomaev, D.V. Shitz, and V.F. Tarasenko, in: *Proc. of the 34th EGAS* (Sofia, Bulgaria, 2002), pp. 345–346.
6. A.A. Lisenko and M.I. Lomaev, Atmos. Oceanic Opt. **15**, No. 3, 265–266 (2002).
7. Z. Falkenstein and J.J. Coogan, J. Phys. D **30**, No. 19, 2704–2810 (1997).
8. M.I. Lomaev, V.F. Tarasenko, and D.V. Shitz, Pis'ma v ZhTF **28**, Is. 1, 74–80 (2002).
9. M.I. Lomaev, E.A. Sosnin, V.F. Tarasenko, D.V. Shitz, V.S. Skakun, M.V. Erofeev, and A.A. Lisenko, Prib. Tekhn. Experim., No. 5, 5–26 (2006).
10. S.M. Avdeev, E.A. Sosnin, and V.F. Tarasenko, Opt. Spektrosc. **103**, No. 4, 554–560 (2007).
11. X. Feng and S. Zhu, Phys. Scr. **74**, 322–325 (2006).
12. M. Neiger, in: *Proc. of 6th Int. Symp. of the Science and Technology of Light Source* (Budapest, 1992), pp. 75–82.
13. N.N. Guivan, J. Janča, A. Brablec, P. Stahel, P. Slavicek, and L.L. Shimon, J. Phys. D **38**, 3188–3193 (2005).
14. D.V. Shitz, M.V. Erofeev, V.S. Skakun, V.F. Tarasenko, and S.M. Avdeev, Prib. Tekhn. Experim. (2008) [in press].
15. A.M. Boichenko, V.S. Skakun, E.A. Sosnin, V.F. Tarasenko, and S.I. Yakovlenko, Laser Phys. **10**, No. 2, 540–552 (2000).
16. S.M. Avdeev, M.V. Erofeev, V.S. Skakun, E.A. Sosnin, A.I. Suslov, V.F. Tarasenko, and D.V. Shitz, Quant. Electron. **38** (2008) [in press].
17. S.M. Avdeev, M.V. Erofeev, E.A. Sosnin, and V.F. Tarasenko, Quant. Electron. **38** (2008) [in press].
18. S.M. Avdeev, G.N. Zvereva, and E.A. Sosnin, Opt. Spectrosc. **103**, No. 6, 946–955 (2007).