TRANSVERSAL RADIO-FREQUENCY DISCHARGE IN THE Xe/Cl_2 MIXTURE

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Results of investigation of a transversal radio-frequency (rf) (f = 1.76 MHz) discharge (TRFD) in the Xe/Cl_2 gas mixture (the gas pressure $P \leq 400$ Pa) are presented. It is shown that the discharge is a high-power wide-band source of uv radiation in the spectral region of 220—450 nm defined by the wide bands of $XeCl(D-X, B-X; B-A, C-A)$ possessing the maxima at, correspondingly, λ = 236, 307, 390, and 430 nm, and the 257-nm band of $Cl_2(D'-A')$. A unified continuum in the spectral region of (220—310) nm has been formed on the basis of the bands of $XeCl(D, B-X)$ and $Cl_2(D'-A')$, as a result of the incompleteness of vibrational relaxation, whereas the bands of $XeCl(B, C-A)$ have formed a less intensive continuum in the region of 320—450 nm. The plasma emission was composed of an rf component and a dc component. A 8-ms macropulse has been formed as a result of discharge initiated by applying a pulsed voltage "filled" with the rf oscillations. Mixtures of $P(Xe)/P(Cl_2) = (400 \div 200/40 \div 30)$ turned out to be optimal for achievement of maximal uv-emission power. Average uv-emission power of the whole working aperture has reached 30—50 W at an efficiency of 10—15%.

The transversal rf discharge may be used in high-power wide-band lamps with planar aperture of the outlet of radiation whose area is at least 100 cm^2.

High-power electric-discharge lamps operating in both the continuous and pulse-periodical modes and emitting from the transitions of mono-halogenides of noble gases of RX^* type (with R being Ar, Kr, or Xe; and X being F, Cl, Br, or I), or the diatomic gas molecules (dimers) of halogens (the X_2^* type), have found a wide application in the field of microelectronics, high-energy chemistry, ecology, and medicine [1—3]. Active media for such emission sources are most widely formed with using the longitudinal glow discharge [4—7] and the pulse-periodical one in a dielectric [8, 9]. In work [10], there have been revealed promising features of the inductance-type rf discharge from the point of view of designing an ecologically-pure XeCl lamp. All the above-mentioned uv radiation sources have the outlet aperture of the cylindrical form, which makes it problematical to use them for a uniform irradiation of flat surfaces. The currently developed planar excimer lamps are based upon the fluorides of noble gases only, and in their realizations there are used the aggressive working media of R/F_2 type. Formation of the active medium in these lamps is achieved with using the microwave discharge fed from a power-supply unit that needs to be matched with the electrodes of an excimer lamp [11, 12]. To realize the excitation of the Xe/Cl_2 gas mixture and fabricate the planar excimer lamp, usage of a volume discharge that is not confined by the dielectric walls, is proposed in work [13]. However, the spectral, life-time, and temporal characteristics of the discharge are not adduced. Employment of the capacity rf discharge in the electro-negative gas media of excimer lamps is promising for its increased resistance against the formation of plasma instabilities as compared with the dc glow discharge. For the time being, there are absent investigations of optical characteristics of the intermediate-pressure transversal rf discharge in the R/Cl_2 mixtures; this restrains a development of high-efficient planar lamps based upon the chlorides of heavy noble gases.

The objective of this work is to investigate characteristics of the transversal rf discharge with bared electrodes in the Xe/Cl_2 mixture, and optimize the energy-conversion characteristics of the plasma-emitted uv radiation as a function of pressure and components of the working mixture.

TRFD has been investigated on the experimental setup presented schematically in Fig. 1. In the experiments, plasma emission spectra in the range of

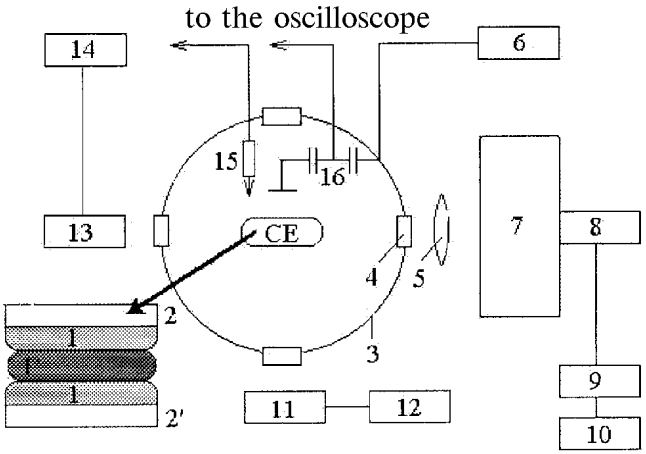

Fig. 1. Experimental setup for investigation of transversal rf discharge: system of electrodes CE; plasma of the electrodes-adjacent layers *1* and of the positive column of rf discharge *1'*; upper *2* and lower *2'* electrodes; discharge chamber *3*; quartz windows *4*; lens *5*, EN-57M high-voltage supply unit *6*; monochromator MDR-2 with ruled diffraction grating of 1.200 grooves per mm *7*; FEU-106 photomultiplier *8*; U5-9 dc amplifier *9*; KSP-4 plotter *10*; receiving head *11* of spontaneous-emission power meter *12* of "Kvarts-01" type; pulsed photomultiplier "Foton" *13*; S1-99 wide-band pulse oscilloscope *14*; shunt ($R_{sh} = 1 \div 5$ Ohm) *15*; capacitive bleeder *16*

200—600 nm, electrode voltage oscillograms, discharge current, plasma emittance, and the power of uv radiation from a lateral surface were measured.

The TRFD initiation has been realized in a volume of $17 \times 3 \times 2.2$ cm (with 2.2 cm being the interelectrode distance). In the experiment, a power supply unit providing the rf ($f = 1.76$ MHz) amplitude-modulated ($F = 50$ Hz) voltage with average power of 300 W was used. The TRFD-initiating electrode system included one nickel-plated brass electrode with 3 cm curvature radius of its working surface, and a plane 0.2 mm-thick nickel electrode. The electrodes were mounted on a dielectric flange and inserted into a 10-liter discharge chamber. The spectra were measured by a Soviet-made monochromator of MDR-2 type (with a diffraction grating of 1200 grooves/mm and spectral resolution of 0.5 nm) and a photomultiplier (PM) of FEU-106 type, calibrated in the relative spectral sensitivity. The pulses of integral emission have been measured with the use of a fast PM "Foton" and oscillograph S1-99. The time-decay curves of discharge-gap voltage were measured with using a small-inductance capacitive voltage divider, and the discharge current oscillograms with using a shunt. The S1-99 oscillograph measured signals of the

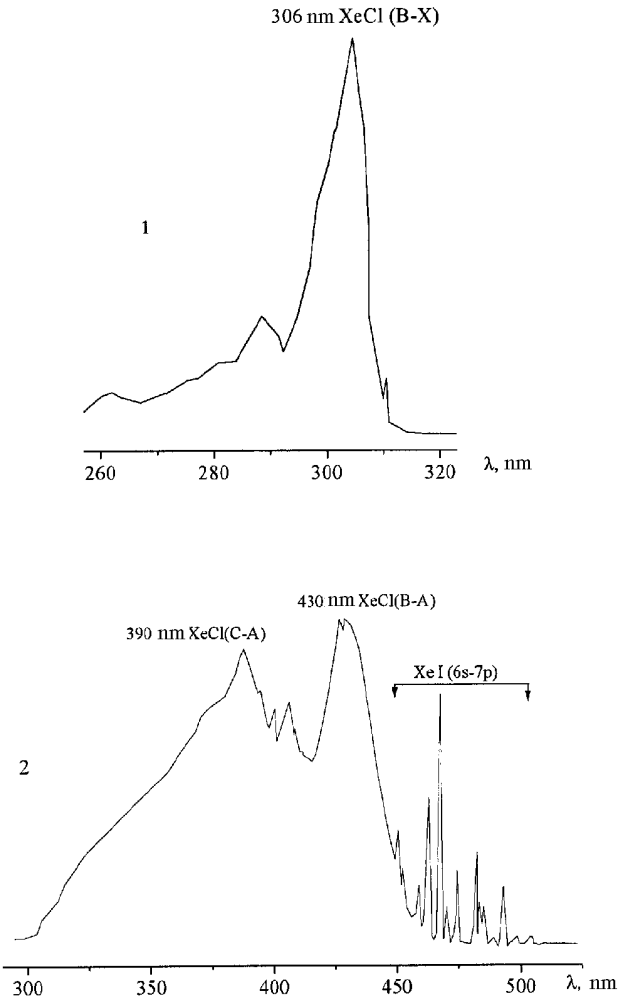

Fig. 2. Emission spectra of Xe/Cl_2-mixture TRFD plasma in the spectral regions of 200—340 nm (*1*) and 300—500 nm (*2*)

voltage divider and shunt. The time resolution in the plasma emission measurements did not exceed 10 ns, and in the voltage and current oscillograms — about 5 ns. The overall uv-radiation output power of the TRFD plasma was measured by a "Kvarts-01" apparatus with using a technique described in work [14].

In Fig. 2, the hardware-controlled emission spectra of the Xe/Cl_2-mixture-based TRFD plasma are presented. Identification of the spectral bands was done in accordance with data of works [15—17] and the spectroscopic tables [18]. The main uv radiation of the plasma was caused by the wide band of $XeCl(B - X)$ ($\Delta\lambda \leq 50$ nm at the bandwidth base level) with the maxima at $\lambda = 289$ and 306 nm. These peaks were overlapping with the less luminous emission bands of 257 nm of $Cl_2(D' - A')$ and 235 nm of $XeCl(D - X)$, which gave a basis for the formation of the most

short-wave part of the continuum. A narrowing of the XeCl($B-X$) band with simultaneous noticeable growth of its luminance was observed under an augmentation of the Xe partial pressure from 40 Pa to 200—400 Pa (with keeping P(Cl_2) to be constant). In these circumstances, the contribution of the 257 nm band of $Cl_2(D'-A')$ into the uv continuum was decreasing. Since a spectrum of this radiation source includes both the excimer bands and the band of a Cl_2 molecule, one could consider this lamp as an excimer-halogen one. In the long-wave section of the spectrum, two wide bands with maxima of 390 nm and 430 nm were observed, which formed (with mutual overlapping) the long-wave edge of the continuous radiation at $\lambda = 450$ nm. The 390 nm band of XeCl($C-A$) was by 2.5 or 3 times wider than the 430 nm band of XeCl($B-A$). The radiation-intensity maxima occurring within the electron-vibrational band of XeCl($C-A$) molecules, were shifted, as compared with the corresponding data for the atmospheric-pressure plasma, to the long-wave edge of the spectrum (from 345 nm [19] to 390 nm), and emission of the XeCl($B-X$) band was not observed at all under an increased pressure of the working mixture [19]. In this case, the main intensity maximum of the XeCl($B-X$) emission band has been shifted from 308 nm [19] to (305.5—306) nm. Such peculiarities of the TRFD-plasma radiation spectra are explained, first of all, by the use of low working pressure of the Xe/Cl_2 mixture, and, second, by the incompleteness of the processes of vibration relaxation taking place within the energy states of XeCl(B,C,D) and $Cl_2(D')$ [20]. These peculiarities allowed the formation of continuous emission in the spectral region of 220—450 nm. We have observed all the most intense maxima of the second positive nitrogen system, $N_2(C-B)$, against the background of the wide $C-A$ band of a XeCl molecule. Partial pressure of the nitrogen did not exceed 10 Pa, and a residual air remaining in the discharge chamber after its preliminary depression by a roughing-down pump caused the mentioned maxima. The visible-region spectrum emitted by the plasma was a line one. It was predominantly formed by the more intense spectral lines of Xe atoms. The most intense spectral line determining the discharge color, was that with a wavelength of 467.1 nm of the XeI component (the transition of $6s[3/2]^0_2$—$7p[5/2]_2$). In the plasma emission spectrum, we have not revealed intense lines of Xe ions.

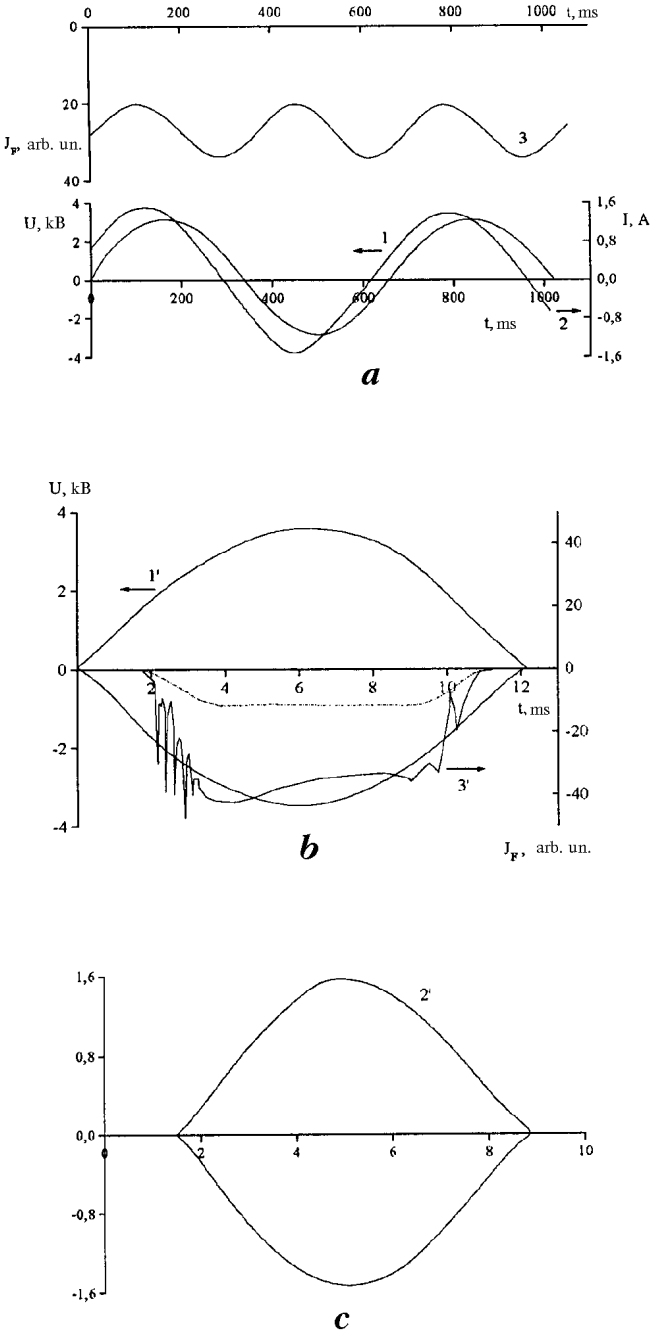

Fig. 3. Oscillograms of voltage (*1*, *1'*), current (*2*, *2'*), and emission (*3*, *3'*) of TRFD plasma based on the mixture with $P(Xe)/P(Cl_2)$=200/80; rf components (*1—3*) are shown for macropulses (*1' − 3'*)

Temporal characteristics of the discharge-gap voltage, current, and radiation of the Xe/Cl_2-mixture-based TRFD-plasma are presented in Fig. 3. Since the excitation source operates in the pulse-periodic mode and generates the rf-filled voltage macropulses whose duration does not exceed 10 or 12 ms, the temporal characteristics of TRFD were investigated at the time-span level of rf oscillations (Fig. 3,*a*), and with averaging

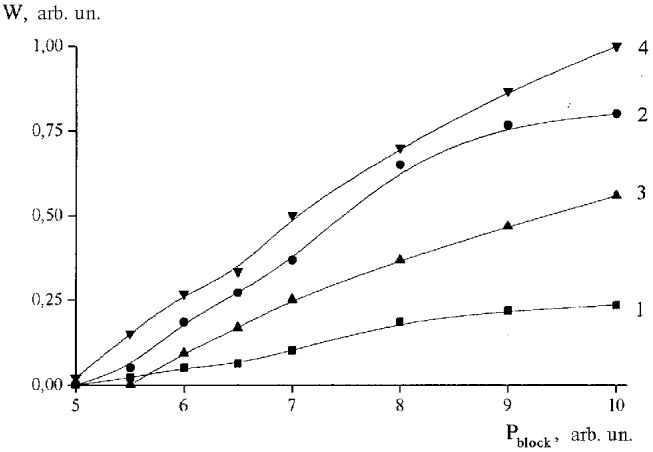

Fig. 4. Dependence of average uv radiation power of the TRFD plasma on electric power of the discharge for various proportions of the mixed gases: $P(\mathrm{Xe})/P(\mathrm{Cl_2}) = 40/80$ (*1*); 200/80 (*2*); 200/160 (*3*), and 200/400 (*4*)

them over the macropulse duration time (Fig. 3,*b*). The broken curve in Fig. 3,*b* shows the lower level of the rf radiation in the macropulse. The half-wave amplitude of the rf voltage oscillation reaches 3 or 4 kV, and the current's one — 1.5 A. The maximal duration of the half wave of voltage or current constituted 300 or 350 ns. The plasma radiation (over the submicrosecond time interval) had a constant amplitude-modulated (by 30 or 35%) component of the doubled frequency ($f = 3.5$ MHz). This may be an indicative of the presence of a channel of continuous formation of excimer molecules in the plasma due to the "harpoon" reaction between the metastable-state Xe atoms and Cl molecules. During the flow of rf current, the density of metastable-state Xe atoms had not been reducing to zero, and this is the cause that keeps the following process to be continuous:

$$\mathrm{Xe}(m) + \mathrm{Cl_2} \longrightarrow \mathrm{XeCl}^* + \mathrm{Cl}. \qquad (1)$$

As follows from Fig. 3, the contribution of the constant component into the TRFD-plasma emission exceeded 70% for the mixture with the pressure relationship of $P(\mathrm{Xe})/P(\mathrm{Cl_2})$=200/80. Let us consider the transversal discharge's characteristics averaged over an rf oscillations period (Fig. 3,*b*). The maximal duration of a voltage macropulse was equal to 12 ms, and of the current — to 7 ms. A breakdown threshold of the discharge gap, which consisted mainly of the electrode-adjacent layers and the cathodic parts of a high-current TRFD, was equal to 2.0 kV. The most long plasma-emitted macropulse reached to 9 ms. At its leading edge, 5 to 7 intense short maxima were observed, whereas at the trailing edge — 2 or 3 maxima of a smaller amplitude. The top of TRFD-plasma emission macropulse was a slowly-rolling-off one that may be explained by a heating of the working mixture and an increasing of the $\mathrm{Cl_2}$ tenuity in it within the time interval of 5 ms. Along with a falling of the Xe partial pressure from 200 to 80 Pa, there were not observed any short flashes of intensity at the edges of the optical macropulse. As follows from works [21—23], in an electronegative-gases-based multicomponent plasma, the jumps of the densities of electrons, positive and negative ions may be formed. These are formed, in general, on the boundary separating plasmas of different types. Recombination of the Xe^+ and Cl^- ions existing in the density jumps' region, may initiate, at certain moments, a formation of short flashes at the leading edge of a macropulse of the TRFD-plasma radiation. Since this TRFD is a high-current discharge (the γ-type rf discharge) existing with the pierced electrode-adjacent layers, it possesses the electrode-adjacent plasma (similar in its properties to that of the cathodic parts of a glow discharge [24, 25]) of two types divided by a positive column. At the interfaces of these regions of different parameters, the density jumps of the Xe^+ and Cl^- ions may occur. At the leading edge of the plasma-emission time-averaged curve, the jump emerges within the time interval of 1.7 to 2.5 ms.

Fig. 4 shows curves of the TRFD-plasma uv radiation power as a function of the discharge-feeding power for various relationships of Xe and Cl in the $\mathrm{Xe}/\mathrm{Cl_2}$ mixture. Augmentation of electric power of the discharge in all the cases leads to increasing the plasma uv radiation power. With increasing the partial Xe pressure from 80 to 200 Pa, the latter power was increased by almost 3 times, whereas increasing of the partial $\mathrm{Cl_2}$ pressure from 40 to 160 Pa led to the reduction of radiation power by a half. In this case, a rise of the threshold value of the discharge-initiation voltage was observed. The mixtures with the relationship $P(\mathrm{Xe})/P(\mathrm{Cl_2})$=(200÷400)/(30÷40) were optimal for reaching a maximal power of plasma uv radiation. The uv power radiated by the plasma through the lateral surface of TRFD reached 30 to 50 W with an efficiency of 10 to 15%.

Hence, the investigation of characteristics of the γ-type transversal rf discharge in the $\mathrm{Xe}/\mathrm{Cl_2}$ mixtures ($P \leq 400 \div 500$ Pa) show that: i) the plasma is a wide-band radiation source that emits in the spectral region of 220—450 nm formed by a pentad of the following bands: 235 nm of $\mathrm{XeCl}(D-X)$, 257 nm of $\mathrm{Cl_2}(D'-A')$, 306 nm of $\mathrm{XeCl}(B-X)$, 390 nm of $\mathrm{XeCl}(C-A)$, and 430 nm of $\mathrm{XeCl}(B-A)$. The plasma emission is a superposition

of a time-continuous component (contributing by 70% or more) and rf ones which may be caused by various mechanisms of the excimer molecule formation; ii) for the threshold-close values of the discharge-feeding voltage, a series of discrete momentary plasma-emission flashes is revealed, which may be caused by the density jumps of electrons, positive and negative ions at the interface between the cathodic parts and the positive column of discharge; iii) the mixture with the pressure relationship of $P(\mathrm{Xe})/P(\mathrm{Cl_2})=(200\div400)/(30\div40)$ is optimal for reaching a maximal power of the wide-band-plasma uv radiation; iv) it is possible to create a TRFD-based planar excimer-halogen lamp possessing the aperture area of at least 100 cm^2, if a mixture of heavy noble gases and chlorine will be used as the active medium.

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ПОПЕРЕЧНИЙ ВИСОКОЧАСТОТНИЙ РОЗРЯД НА СУМІШІ КСЕНОНУ З ХЛОРОМ

О.К. Шуаібов, Л.Л. Шимон, А.Й. Дащенко, І.В. Шевера

Р е з ю м е

Наведено результати дослідження поперечного високочастотного розряду (ПВЧР) ($f = 1,76$ МГц) в суміші ксенон/хлор ($P \leq 400$ Па). Показано, що він є потужнім широкосмуговим джерелом УФ-випромінювання в спектральному діапазоні 220—450 нм, спектр випромінювання якого визначається широкими смугами $XeCl(D-X, B-X; B-A, C-A)$ з максимумами відповідно при $\lambda = 236$, 307, 390, і 430 нм і смуги 257 нм $Cl_2(D'-A')$. Внаслідок незавершеності процесів коливальної релаксації на основі смуг $XeCl(D, B-X)$ та $Cl_2(D'-A')$ формувався єдиний континуум в діапазоні 220—310 нм, а смуги $XeCl(B, C-A)$ утворювали менш яскравий континуум в діапазоні 320—450 нм. Випромінювання плазми складалося з високочастотної і постійної складових. В результаті живлення розряду імпульсами напруги, які були заповнені високочастотними періодичними коливаннями, формувався макроімпульс випромінювання тривалістю 8 мс. Для одержання максимальної потужності УФ-випромінювання найбільш оптимальними були суміші $P(\mathrm{Xe})/P(\mathrm{Cl_2}) = (400 \div 200/40 \div 30)$. Середня потужність УФ-випромінювання з усієї робочої апертури досягала 30—50 Вт при коефіцієнтах корисної дії 10—15%. Поперечний високочастотний розряд може бути використаний в потужній широкосмуговій лампі з планарною апертурою виводу випромінювання, площа якої не менша ніж 100 $\mathrm{см}^2$.