OPTICAL CHARACTERISTICS OF GAS-DISCHARGE PLASMA OF ATMOSPHERIC PRESSURE BARRIER DISCHARGE ON ZINC DIIODIDE VAPOR WITH HELIUM MIXTURES

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Investigations of the optical characteristics of a gas-discharge plasma of an atmospheric pressure barrier discharge on mixtures of zinc diiodide vapor with helium are presented. The repetition rate of the plasma pumping pulses was 130 kHz. The regularities were established: in the emission spectra of a barrier discharge plasma in the 400…750 nm range with a resolution 0.05 nm, in the temporal characteristics of voltage and current, and the radiation brightness dependences on the partial pressure of helium and nitrogen. The emission of exciplex ZnI* molecules with a maximum of intensity at λ = 602 nm, excimer molecules I_2^*, and lines of zinc and helium atoms was revealed. The specific average radiation power in the spectral range Δλ = 550…650 nm was determinedwhich and it is equal to 34 mW/cm^3.

PACS: 42.55.Lt; 42.60 Lh

INTRODUCTION

Data on the optical characteristics of a gas-discharge plasma on mixtures of zinc diiodide vapor with helium are important for the diagnosis and optimization of the spectral and energy characteristics of sources of spontaneous (excilamp) and coherent radiation (lasers). Mixtures of zinc diiodide vapor with inert gases can be promising working media for creating environmentally friendly spectral radiators in the visible and ultraviolet spectrum range. Investigations of the optical characteristics of such radiators on mixtures of zinc diiodide vapor and helium under gas-discharge plasma conditions and optical pumping are presented in [1-5]. In this case, the repetition rate of the generator pulses that excited the plasma was ≤100 kHz. To create powerful narrow-band sources of visible and ultraviolet radiation, it is of interest to study optical characteristics at higher frequencies of plasma excitation, which was the purpose of our studies. In this paper, studies are made of the optical characteristics of atmospheric pressure gas-discharge plasma on mixtures of zinc diiodide vapor and helium and a small addition of molecular nitrogen at a pump pulse repetition rate of 130 kHz.

1. THE TECHNIQUE AND METHODS OF THE EXPERIMENT

The technique and methods of the experiment were similar to those used in the study of the optical characteristics of a gas-discharge plasma ofan atmospheric pressure barrier discharge on mixtures of zinc diiodide vapor with helium [6].

2. RESULTS AND DISCUSSION

Typical oscillograms of current and voltage are shown in Fig. 1. In each half-period of the applied voltage on the oscillogram of the detected current, a series of sharp picks of different amplitudes and about the same duration was observed on the displacement current curve. Each current pick is caused by a set of filamentary microdischarges - filaments that occur in the discharge gap and are statistically distributed in time.

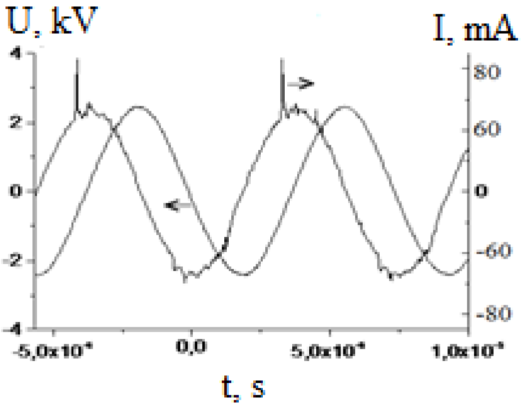

Fig. 1. Oscillograms of voltage and current pulses of a gas-discharge plasma of a barrier discharge in a ZnI_2 / He = 0.5 Pa/150 kPa mixture

The oscillogram of the current pulses is asymmetric- in the positive half-cycle, the first burst had a much larger amplitude than the others, and in the negative half-cycle the amplitude of all the bursts was approximately the same. This is apparently due to the fact that with increasing frequency in the DBD on the mixture, the role of the factors associated with the discharge geometry significantly increases, namely, the surface areas of the electrodes are very different, since the discharge occurs in the "cylinder-wire" system, the dielectric is covered only one electrode of the radiator, and in one case the charge transfer occurs first through the dielectric barrier, and then through the plasma, and in the other way around - first through the plasma, and then through the dielectric.

A typical survey spectrum of the radiation of DBD plasma on a mixture of zinc diiodide vapor with helium is shown in Fig. 2. In the spectra obtained in the visible range, a band with a maximum at λ = 602 nm was distinguished, which had a poorly-resolved vibrational structure and corresponded to the $B^2\Sigma^+_{1/2} \rightarrow X^2\Sigma^+_{1/2}$electron-vibrational transition of the ZnI molecule [7].

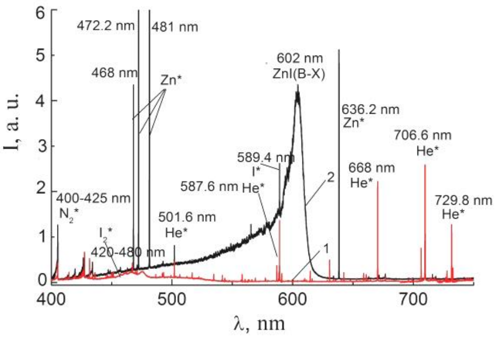

Fig. 2. The survey spectrum of the radiation of a gas discharge plasma of a barrier discharge on mixtures:
1 – ZnI_2 / He = 0.0003 Pa / 150 kPa (cold mixture);
2 – ZnI_2 / He = 0.5 Pa / 150 kPa

The bulk of the radiation of ZnI(B→X) molecules is concentrated in the range of 590…608 nm. The shape of the ZnI (B→X) band is similar to the spectral bands corresponding to the B→X transition in mercury monohalides, namely: a steeper increase in intensity from the long-wave range anda slow decline in the short-wavelength region. At atmospheric pressure of the mixture, due to the completion of vibrational relaxation, the transitions occur mainly from the lower vibrational levels of the excited electronic state. The width at half-height for the spectral band of ZnI (B→X) was 15 nm, which agrees with the results of [1], where the optical pumping of the ZnI_2/Ar mixture by ArF laser radiation was used. Also in spectra there were atomic zinc lines - 5s → 4p (468.0, 472.2 and 481.0 nm) triplet, 4d →4p (636.2 nm) line [8] and molecular iodine bands, the most intense of which was band I_2 (D'-A ') with a maximum at λ = 342 nm [7]. The intensity of the atomic lines and the brightness of the molecular bands strongly depended on the temperature of the working mixture. The intensity of the zinc lines increased with increasing temperature, while the brightness of the bands of molecular iodine decreased. The brightness of the molecular band was understood as the area under the curve on the spectrum.In the spectral region 315…425 nm, molecular nitrogen bands corresponding to the electronic-vibrational transition $C^3\Pi_u \rightarrow B^3\Pi_g$ of the second positive N_2 system were also observed. They were manifested in the spectrum due to burningof the discharge (parasitic) in the air between the outer surface of the quartz tube and the grid. At a temperature <100…120 ^{0}C, in the range 420…480 nm, bands that are identified with the emission of I_2 molecules (B→X) were observed (see Fig. 2). In the emission spectrum of the DBD (see Fig. 2), the intensity of the helium atomic lines noticeably decreased as the working mixture warmed up. This regularity is due to a decrease in the electron temperature in the discharge with an increase in the concentration of readily ionizable particles, in particular, zinc diiodide molecules and zinc atoms. [9].

When the helium partial pressure in the ZnI_2 / He mixture was increased from 102 to 200 kPa, the brightness of the ZnI (B→X) radiation increased approximately three times without signs of saturation (Fig. 3). Such a dependence can be caused by an increase in the temperature of the working mixture and, in turn, by an increase in the partial vapor pressure ZnI_2. Addition of nitrogen to the ZnI_2 / He mixture (the inset in Fig. 3) led to a monotonous decrease in the intensity of the ZnI molecules, since the energy of the discharge is expended on additional channels, including vibrational excitation of molecular nitrogen.

The emission of spectral bands and barrier discharge plasma lines on a mixture of zinc diiodide vapor and helium is probably observed due to the following reactions: [10, 11]:

$$ZnI_2+e\rightarrow ZnI_2(^{3,1}\Sigma^+_u)\rightarrow ZnI(B^2\Sigma^+_{1/2})+I+e, \tag{1}$$

$$ZnI_2+e\rightarrow ZnI_2(^{3,1}\Sigma^+_u)\rightarrow ZnI(B^2\Sigma^+_{1/2})+I^-, \tag{2}$$

$$ZnI_2+e\rightarrow ZnI_2\ (D)\rightarrow ZnI\ (C^2\Pi_{1/2}, D^2\Pi_{3/2})+I+e, \tag{3}$$

$$ZnI\ (C^2\Pi_{1/2}, D^2\Pi_{3/2})+M\rightarrow ZnI(B^2\Sigma^+_{1/2})+M+\Delta E_{1,2}, \tag{4}$$

$$ZnI_2+e\rightarrow ZnI(^{3,1}\Sigma^+_u)\rightarrow ZnI(X\,^2\Sigma^+_{1/2})+I+e, \tag{5}$$

$$ZnI(B^2\Sigma^+_{1/2})\rightarrow ZnI(X\,^2\Sigma^+_{1/2})+h\nu, \tag{6}$$

$\lambda_{\text{макс.}}$ = 602 nm,

$$ZnI(B^2\Sigma^+_{1/2})+M\rightarrow ZnI(X\,^2\Sigma^+_{1/2})+M+\Delta E_3, \tag{7}$$

$$ZnI_2+e\rightarrow Zn^*+2I\ (I_2^*, I_2, I_2^-)+e, \tag{8}$$

$$I_2(D')\rightarrow I_2(A'), \tag{9}$$

$\lambda_{\text{макс.}}$ = 342 nm,

$$I_2(B)\rightarrow I_2(X), \tag{10}$$

$\lambda_{.}$ = 420 – 480 nm,

$$Zn^*\rightarrow Zn+h\nu \tag{11}$$

λ=468.0, λ=472.2 nm, λ=481.0 nm , λ=636.2 nm,

$$I^*\rightarrow I+h\nu, \tag{12}$$

$\lambda_{.}$ =589.4 nm,

$$He+e\rightarrow He^*+e, \tag{13}$$

$$He^*\rightarrow He+h\nu, \tag{14}$$

λ=501, 6 nm,

$$He^*+M\rightarrow He+M+\Delta E_4, \tag{15}$$

where M is the concentration of quenching molecules and atoms (ZnI_2, He,), respectively, $\Delta E_{1,2}$ – energy difference in reactions (4), ΔE_3, ΔE_4-energy difference in reactions (7) and (15).

In addition, the formation of ZnI (B) molecules can also occur in electron-ion and ion-ion recombination reactions. But the contribution of such processes is insignificant because of lower concentrations of the initial components [10].

Reactions (1) and (2) are known as the main sources of exciplex molecules of zinc monoiodide (ZnI*), which rate constants are not known at the moment. It can be assumed that they are within the limits of 10^{-15} m^3/ s and 10^{-17} m^3/s, respectively, since the specific radiation power in the spectral band of the exciplex ZnI* molecule (Fig. 4) is close to the specific radiation power in the spectral band of exciplex molecules mercury monoiodide and mercury monobromide [12]. In addition, molecules of zinc monoiodide can be formed in reactions (3) due to the excitation of molecules of zinc diiodide to state D in collisions with electrons (D-state is the sum of several states that are located between 7 and 13 eV (ionization threshold ZnI_2) [2, 10].

Emission from the D-state of ZnI_2 is not observed, since this state rapidly dissociates with the formation of electronically excited ZnI^* molecules in C and D-states [10]. They are quenched in reaction (4), leading to a high population – the state $B^2\Sigma^+_{1/2}$ of zinc monoiodide [10]. The reaction of the collision of molecules of zinc diiodide with electrons (6) is a channel for the formation of molecules of zinc monoiodide in the ground state $X\,^2\Sigma^+_{1/2}$, the rate constant of which, according to our estimate, is ~ 10^{-15} m^3/s. Electron-vibrational transitions $B^2\Sigma^+_{1/2} \rightarrow$ ($X\,^2\Sigma^+_{1/2}$) ofzinc monoiodidemolecules lead to the emission of spectral bands with maximum intensity at a wavelength of $\lambda_{max.}$ = 602 nm (reaction (6)) [10]. Emission of spectral bands with a maximum intensity at a wavelength $\lambda_{max.}$ = 342 nm is caused by the electron-vibrational transition D '→ A' of iodine molecules (reaction 9), and the emission of spectral bands at λ = 420…480 nm is caused by the electronic-vibrational transition B →X of iodine molecules (reaction 10) [10]. Excited iodine molecules are formed in reaction (8). Excited zinc atoms are formed due to the passage of reactions (8) due to the large effective cross section for the dissociative excitation of molecules of zinc diiodide with electrons [11]. The reaction (13) is responsible for the excitation of the atoms of the helium buffer gas. An important role in the emission of spectral bands and lines belongs to the quenching processes from which emission occurs both by zinc diiodidemolecules (reaction 7) and by atoms of the buffer gas helium (reaction 15), because of which the radiation intensity decreases, the rate constants of which have the value $1.7 \cdot 10^{-9}$ m^3 / s and ~ $1.5 \cdot 10^{-11}$ m^3 / s [2].

Measurement of the average radiation power W of the radiator was carried out at a total pressure of 150 kPa (see Fig. 4). After the discharge was switched on with increasing temperature, the average power initially increased during 12 minutes after which a slight decrease in W for 8 min was caused by a decrease in the intensity of emission of inert gas lines and spectral bands of molecular iodine (see Fig. 3). Then the radiator entered the regime in 20 minutes and W was stabilized.

Under these conditions, the maximum value of the average radiation power per unit area in the visible range was 34 mW/cm^3 (see Fig. 4), the efficiency with respect to the power input into the discharge was ~ 8 %.

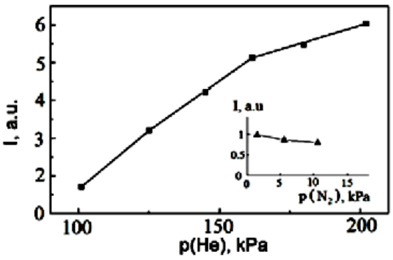

Fig. 3. The dependence of the emission brightness of the spectral band ZnI (B-X) on the value of the partial pressure of helium in the ZnI_2/He mixture. The inset shows the dependence of the emission brightness of the spectral band ZnI (B-X) on the partial nitrogen pressure

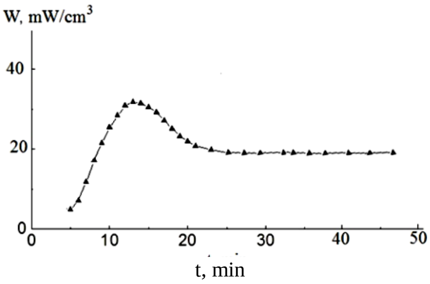

Fig. 4. The dependence of the radiation power of a gas-discharge barrier-discharge plasma on a ZnI_2 / He = 0.5 Pa/150 kPa mixture on the discharge burning time in the range Δλ = 550…650 nm

CONCLUSIONS

Thus, as a result of complex studies of the optical characteristics of atmospheric pressure DBD plasma atmospheric pressure on mixtures of zinc diiodide vapor with helium, intense emission of a spectral band with a maximum at λ = 602 nm of exciplex molecules of zinc monoiodide, the bulk of which is concentrated in the wavelength range 590…608 nm. In addition, spectral bands of molecular iodine were detected, the most intense of which was the band I2 (D'→A ') with a maximum at λ = 342 nm and spectral bands of the B→X electron-vibrational transition in the wavelength range 420…480 nm, and also the zinc line – a triplet of 5s → 4p (468.0, 472.2 and 481.0 nm) and a 4d → 4p (636.2 nm) line.

The average radiation power per unit volume was 34 mW/cm^3 in the wavelength range Δλ = 550…650 nm, the efficiency with respect to the power input to the discharge was ~ 8 %.

A radiator based onatmospheric pressure DBD plasma with high-frequency pumping of a working mixture of zinc diiodide vapor with helium can be the basis for creating a self-heating excilamp that emits in the orange spectral range. Scaling of the working area of the barrier discharge will make it possible to use the radiator in biotechnology, medicine, etc.

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Article received 13.09.2018

ОПТИЧЕСКИЕ ХАРАКТЕРИСТИКИ ГАЗОРАЗРЯДНОЙ ПЛАЗМЫ БАРЬЕРНОГО РАЗРЯДА АТМОСФЕРНОГО ДАВЛЕНИЯ НА СМЕСЯХ ПАРОВ ДИЙОДИДА ЦИНКА С ГЕЛИЕМ

А.А. Малинина, А.Н. Малинин, А.К. Шуаибов

Представлены исследования оптических характеристик газоразрядной плазмы барьерного разряда атмосферного давления на смесях паров дийодида цинка с гелием. Частота следования импульсов накачки плазмы составляла 130 кГц. Установлены закономерности в спектрах излучения плазмы барьерного разряда в диапазоне 400…750 нм с разрешением 0,05 нм, во временных характеристиках напряжения и тока, в зависимостях яркости излучения от парциального давления гелия и азота. Выявлено излучение эксиплексных молекул ZnI* с максимумом интенсивности при $\lambda = 602$ нм, эксимерных молекул I_2^*, линий атомов цинка и гелия. Определена удельная средняя мощность излучения в спектральном диапазоне $\Delta\lambda = 550…650$ нм, которая имела величину 34 мВт/см^3.

ОПТИЧНІ ХАРАКТЕРИСТИКИ ГАЗОРОЗРЯДНОЇ ПЛАЗМИ БАР'ЄРНОГО РОЗРЯДУ АТМОСФЕРНОГО ТИСКУ НА СУМІШАХ ПАРІВ ДІЙОДИДУ ЦИНКУ З ГЕЛІЄМ

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Представлено дослідження оптичних характеристик газорозрядної плазми бар'єрного розряду атмосферного тиску на сумішах парів дійодиду цинку з гелієм. Частота проходження імпульсів накачки плазми становила 130 кГц. Встановлено закономірності у спектрах випромінювання плазми бар'єрного розряду в діапазоні 400…750 нм з роздільною здатністю 0,05 нм, у часових характеристиках напруги і струму, у залежностях яскравості випромінювання від парціального тиску гелію і азоту. Виявлено випромінювання ексиплексних молекул ZnI* з максимумом інтенсивності при $\lambda = 602$ нм, ексимерних молекул I_2*, ліній атомів цинку і гелію. Визначено питому середню потужність випромінювання в спектральному діапазоні $\Delta\lambda = 550…650$ нм, яка мала величину 34 мВт/см^3.