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High-current photoemission glow discharge in Xe–Cs mixture

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An unusual high-current photoemission glow discharge was discovered in Xe–Cs mixture. Its burning voltage is several times lower, while the current density is 1–2 orders of magnitude higher than those of a regular glow discharge in pure xenon and cesium. Such discharges developed in cesium illuminating lamps of pulse-periodic discharge when they were heated by the alternating voltage before the supply of high-current operating pulses at a xenon pressure of 20 torr and within a wide range of cesium pressures from 10^{-6} to 1 Torr. Such discharges may be caused by photoemission from W–Th–Cs structures on the electrodes under the influence of strong UV radiation from the cathode layer.

Keywords: glow discharge; xenon; cesium; mercury-free illuminating lamps; photoemission; thermal emission; UV radiation; cathode layer; current-voltage characteristic.

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Introduction

High-pressure cesium illuminating lamps of high-current pulse-periodic discharge (PPD) feature a very successful combination of characteristics: they are mercuryfree (environmentally safe), quite energy efficient (luminous efficacy up to 60–70 lm/W), and provide the light of exceptionally high quality (color rendering index R_a up to 95–98) with a spectrum approaching the solar one not only in the visible but also in the near UV band [1–3]. The latter feature allows them to be used in the Far North regions for indoor lighting along with compensation for ultraviolet deficiency [4]. Another advantage of lamps under consideration is that, at high working pressures of cesium vapor (P_{Cs} ~ 100 Torr), the surface of the electrodes that are usually made of thoriated tungsten, adsorb cesium (in addition to thorium) that contributes to reduction of the work function much more considerably than thorium itself - down to 1.6–1.7 eV [5]. When the lamp is powered with alternating-polarity pulses (to maintain approximately the same thermal state of both electrodes), both of them are heated up to the temperatures of about 1200–1500 K, which is quite enough for ensuring the working pulse currents of 50–100 A due to thermal emission, without the formation of erosive cathode spots. This operation mode of electrodes allows expecting long service lives of cesium lamps if the relevant electronic start equipment (ESE) will generate not only operating high-current pulses (like it was during its prototype tests [3]) but also ensure pre-heating of the discharge volume in the glow discharge mode upon lamp turning-on. As soon as the proper temperature of electrodes and "cold point" of the discharge tube (burner) that determines the cesium vapor pressure are reached, the lamp power circuit shall switch over to the mode of operating pulses delivery. Obviously, designing of such ESE firstly requires clarifying specific features of glow discharge ignition and development for "cold" lamps having a room temperature. This is the task of this work.

Experiment procedure

The heating was researched using two lamps with burners of different sizes. One lamp was a laboratory model where the discharge tube was placed in a pumped quartz tube with electrodes led out through rubber seals. The effective volume of the lamp was pumped using a backing vacuum pump with a nitrogen trap up to reach the pressure of ~ 10^{-4} torr. The discharge tube (see the photo in Fig. 1) made of monocrystal sapphire had internal diameter $2r = 11$ mm. The experimental design included identical wire electrodes made of thoriated tungsten and wound over the core that had the working surface area of 1 cm^2. The distance between electrodes in this specimens was $L = 35$ mm (hereinafter burner 11/35).

The second lamp under research was single-capped, fit with an evacuated bulb and a much smaller burner: $2r = 5$ mm, $L = 22$ mm (hereinafter burner 5/22), with the working surface area of its electrodes equaling to ~ 0.25 cm^2. External heating using a Nichrome helix could be carried out on the sealed tube. In both cases the burning gas is xenon which pressure at the room temperature was $P_{Xe} = 20$ Torr, which corresponds to the atom concentration of $N_{Xe} \approx 6\times10^{17}$ cm^{-3}. At the temperature of 20 °C, the equilibrium of cesium vapor pressure over its liquid phase is very low – $P_{Cs} \sim 3\times10^{-7}$ torr ($N_{Cs} = \sim 10^{9\ cm-3}$). For this reason, during heating, P_{Cs} is changing within very wide range, up to 1 torr ($N_{Cs} = 10^{16}$ cm^{-3}) at the burner temperature of ~ 600 K, though cesium in the discharge remains a small, easily ionized additive.

The experiment procedure was made as close as possible to the actual operating conditions of ESE. The regulated AC mains voltage was supplied via the step-up transformer to the lamp connected to the line comprising the in-series active and inductive ballasts and a current shunt. In its turn, the voltage from the lamp was supplied to the horizontal deflecting plates of the oscilloscope while the voltage from the current shunt was supplied to the vertical plates, thus enabling the continuous monitoring of the lamp's current-voltage characteristic on the screen. To research the heating, the ballast resistance was set to the value limiting the discharge current immediately after ignition to the level under 1 A thus preventing an arc with an erosive cathode spot. After that the line voltage was supplied to the lamp and smoothly (but fast enough to minimize heating of the cesium film condensing on the internal wall of the discharge tube upon lamp switching-off [6]) until the moment when the discharge glow appears in the interelectrode space. The amplitude of the voltage supplied at this moment was registered as the voltage of discharge ignition in the cold lamp, and was then increased so that to ensure the desired initial heating current. Increasing this current and switching over to the conditions of abnormal glow discharge was supposed to allow determining the maximum permissible currents and voltages at which cathode spots do not develop yet.

Results of measurements and discussion

Fig. 1 and 2 show the discharge evolution while the lamp with burner 11/35 was being heated, that is the photos of the discharge glow and family of dynamic current-voltage characteristics. As can be seen in Fig. 1, the glowing pattern of the discharge after ignition and during the entire heating is really typical for the glow discharge, which means a distinct positive column with a brighter discharge channel of the diameter determined by the tie to the electrodes and an intensive white cathode glow. The thickness of the latter was significantly decreasing as the burner temperature was growing and, as a result, the cesium vapor pressure was increasing. The current-voltage characteristics of the lamp (Fig. 2) have two symmetrical parts corresponding to the positive and negative semiperiods of the heating voltage, each consisting of two branches: discharge branch (which is the actual current-voltage characteristic of the discharge) with the current growing so fast that is can be considered almosxyt vertical, and the pre-ignition one. The slope of the pre-ignition branch is similar for the positive and negative branches of the current-voltage characteristic and is determined by resistance of the cesium film adsorbed on the discharge tube surface (its thicker, nontransparent part can be well seen on photos, Fig. 1). Both discharge branches are almost similar, and their minor difference is likely to be caused by the difference in design of electrode assemblies and dissimilar heat removal via lead wires. They could be regarded as the starting sections of also virtually vertical current-voltage characteristic of the normal mode of the usual glow discharge while the ignited discharge – as the glow discharge in xenon. However, such interpretation comes at odds with the relatively high discharge currents at the vertical branch end of the current-voltage characteristic, associated low voltages and, which is the most important, unproductive attempts to change over to the abnormal mode.

Actually, the maximum current on the characteristics in Fig. 2 is 0.08 A. If we evaluate the area of cathode glow contact with the electrode by the type of cathode glow, then this area shown in the first two photos corresponds to the end surface of the niobium bushing ~ 1 cm^2, and therefore the normal current density reduced to pressure j_n / P_{Xe}^2 is ~ 200 μA/Torr^2. This exceeds by an order of magnitude the same parameter of the glow discharge in pure xenon (16 μA/Torr^2 [7]). But if discharge branches remained vertical until the currents ~ 1 A, when switching over to the mode of abnormal glow discharge was attempted, the difference becomes as high as two orders of magnitude. The difference of several times is also observed between the normal voltage of the glow discharge, which, in xenon, is equal to 306 V, and in cesium – to 340 V [7], and the vertical branch voltage, which is as early as during the first seconds of heating (for the yet cold lamp) proves to be much lower ~ 50 V and remains virtually unchanged during heating (Fig. 2). Such significant difference proved the fact that, even at minimum concentrations of cesium atoms, the unusual discharge is ignited in the Xe–Cs system.

The changing pattern of current-voltage characteristic and discharge glow configuration were reproduced similarly during heating of the sealed tube with a much smaller burner sized 5/22, the research results of which are shown in Fig. 3. The current-voltage characteristic corresponding to the initial heating stage (photo a1) was likely to have two symmetric discharge branches at virtually the same voltage of 50 V.

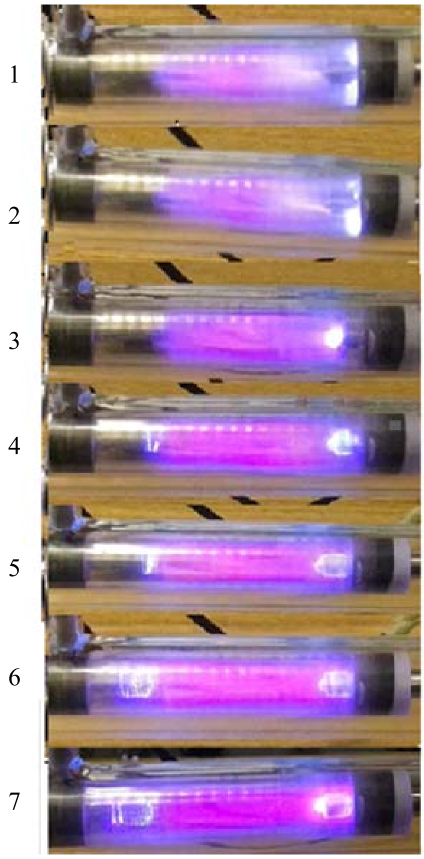

Fig. 1. Evolution of discharge glow during heating of the lamp with burner 11/35. Time after breakdown 1 – 12 s; 2 – 16 s; 3 – 1 min.; 4 – 1 min. 25 s; 5 – 2 min. 14 s; 6 – 3 min.; 7 – 4 min. After that the glow does not change for up to 10 min.

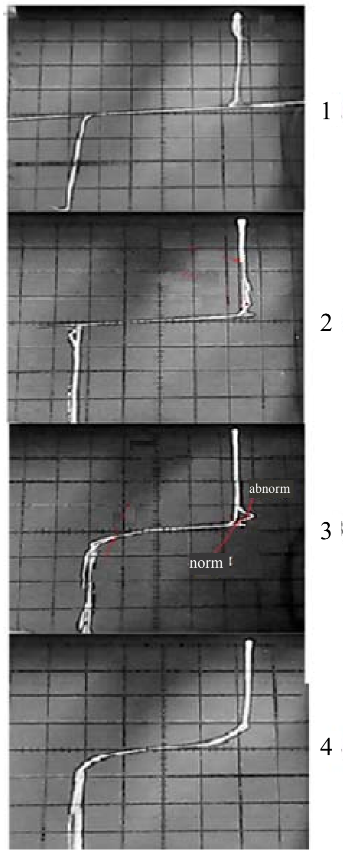

Fig. 2. Change of lamp's current-voltage characteristic during heating. Scale: x = 20 V/div., y = 50 mA/div., zero at the center of the coordinate axes on the screen. t: 1 – 1 s; 2 – 1.5 min.; 3 – 2 min.; 4 – 3 min., after that the current-voltage characteristic does not change for up to 10 min.

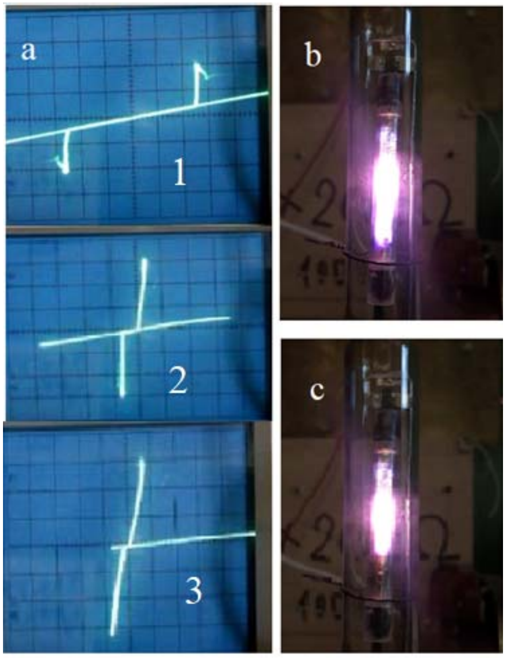

Fig. 3. Evolution of the current-voltage characteristic during heating of the lamp with burner 5/22: 1 – 3 min.; 2 – 7 min.; 3 – 8 min. 30 s from the start of heating. Scale: 1 – 20 V/div and 100 mA/div; 2, 3 – 100 V/div and 100 mA/div

These characteristics agree with the symmetric discharge glow (photo b1) when the cathode glow envelops both electrodes almost similarly. The initial heating current in this mode was noticeably higher and equaled to 0.15 A, increasing up to 0.32 A by the end of this process, which is 4 times as high than in the case shown in Fig. 1. Since the diameter of the positive column's discharge channel, which is associated with electrode sizes, is ~ 2.5 times smaller for burner 5/22, the maximum current density and, therefore, the plasma concentration in the column is approximately 20 times higher for the mode shown in Fig. 3. The high concentration of ions explains the white-pink color of the discharge glow in this burner. The concentration of cesium ions in this discharge state seems to be already high enough for recombination continua to contribute significantly to the radiation of the positive column plasma.

The most important thing when heating of burner 5/22 was that increase of the heating current along with the relatively small burner size, which allowed to increase the electrodes temperature and cesium pressure to the value at which the discharge was able to change over to the arc mode, with the burner voltage dropping from 50 V to several volts and the discharge branch of the current-voltage characteristic developing a noticeable slope. The processes that could be observed visually took place at first with the first electrode (Fig. 3, 2a, 2b). Here the cathode glow enveloping the electrode changed to the end tie to the electrode. Since there was no bright point (cathode spot), the tie was mostly diffuse, that is the cathode current was maintained by the thermal emission of heated electrode. Breakdown was immediately followed by arcing: at first for one electrode, and then for both (current-voltage characteristic 3a in Fig. 3). For burner 5/22, the end surface area of the niobium bushing ~ was 0.25 cm^2, and the reduced normal current density j_n / P_{Xe}^2 ~ was 2000 μA/torr^2 at the end of the vertical section, becoming an order of magnitude higher when attempting to change over to the abnormal mode.

Since the current-voltage characteristic of the discharge almost does not change during heating of the lamp when the concentration of Cs atoms grows by several orders of magnitude, the above specific features of the discharge in xenon with cesium shall be mainly related to the change in emission characteristics of electrodes as they adsorb Cs atoms. For the cesium adsorbed coating to be formed on the surface of electrodes, quite minimum concentrations of Cs atoms in the burner volume suffice, especially that coatings are quite stable at a low temperature of the adsorbing surface (about the liquid-phase temperature of cesium and lower). Whereas decrease of the work function down to $\phi_k \approx 1.7$ eV shall result in the increase of both ion-electron and photoelectric emissions.

When energies of bombarding ions are low $\varepsilon_i < \sim 1$ keV, the emission occurs based on their ionization energy E_i [8]. Ion is neutralized on the surface by the metal's conduction electron with energy consumed ϕ_k and with an excited atom formed, after which the remaining energy $E_i - \phi_k$ is transferred to another conduction electron as the atom is de-excited. And if $E_i - \phi_k > \phi_k$, this electron has a probability of exiting the metal. This higher the difference, the higher such probability is. Similarly, an excited atom with excitation energy $E^* > \phi_k$ getting on the metal surface is able to cause the electron emission.

According to [8], as tungsten is being bombarded, the ion-electron emission factor for ion Xe^+ ($E_i = 12.3$ eV) is virtually constant for the entire range of low ε_i and not high – $\Upsilon_i = 0.02$, because for polycrystalline W $\phi_k \approx 4.7$ eV, and the exceedance $E_i - 2\phi_k = 2.9$ eV is low. But if Cs atoms are adsorbed on the surface and $\phi_k = 1.7$ eV, $E_i - 2\phi_k = 8.9$ eV, and Υ_i shall increase significantly. According to empirical dependence $\Upsilon_i(E_i - 2\phi_k)$ given in [8], we will have Υ_i (9 eV) $\approx$ 0.12. Therefore, during adsorption of cesium on the electrodes, the ion-electron emission for xenon shall increase considerably due to Xe+ ions. While for Cs^+ ions $E_i - 2\phi_k = 3.89 - 3.4 \approx 0.5$ eV is very low. Correspondingly, both Υ_i and their contribution to the electron emission shall be low as well. This explains the weak dependence of the current-voltage characteristic on the cesium pressure during lamp heating, although Cs atoms are easily ionized due to the Penning process.

But if ionization is the main source of cathode electrons, even its strong growth during adsorption of cesium on the electrodes surface cannot explain why the current-voltage characteristic is vertical and abnormal mode does not develop. Indeed, in this case the discharge current is carried by ions both at small and at large ϒi in the high-field region. The difference is that in the first case the generation of one electron requires many ionizations in the high-field region while in the second case fewer ionizations are required. For this reason, the higher density of the ion current is required in this region to increase the discharge current after the point of the normal mode changing to the abnormal one at any Υ_i. The positive space charge and potential drop along the high-field region will increase correspondingly to extent the increased ion current. This determines the voltage growth as the current on the current-voltage characteristic of the discharge's abnormal mode is growing no matter how high ϒ is. These considerations are confirmed by the fact that ϒi is almost the same for argon with pure tungsten as for W–Xe+Cs, even reaching 0.2–0.3 for Ne and He, but the glow discharge for all these pure gases has a clearly defined anomalous section of the current-voltage characteristic.

Whereas the second factor, which is the increase in photoemission when there is an adsorbed layer of Cs on the electrodes surface, can be, in fact, the reason for the absence of the discharge's abnormal mode in the Xe+Cs mixture. But this requires assuming photoemission growth to the value, at which this mechanism becomes the main one ensuring the electron current from the cathode. In this case the current in the high-field region is carried by the electrons emitted by the cathode, and to increase the discharge current, the same cathode's electron emission is required. But this will require the growing number of excitations of Xe atoms followed by the glow rather than the increase in the number of ionizations. The discharge structure remains while parameters change completely, Due to the fact that no intensive ionization is required in the cathode layer, the cathode voltage drops from 300 V to 50 V. Such insignificant drop is likely to result in significant decrease of the electric field strength near the cathode, which means that the energy of accelerating electrons will be mostly consumed for excitation of Xe atoms and generation of resonance radiation that ensures the emission of electrons from the cathode rather than their ionization. But since the cathode drop still noticeably exceeds the ionization potential of the Xe atom, the low ion current is maintained. When its contribution to the discharge current is negligibly small, it is quite likely that it will not only compensate for the space charge of the electron current, but also retain a small positive charge in the high-field region, since the contribution of the Xe^+ ion to the space charge in $(M/m)^{1/2}$ is ≈ 500 times greater than that of the electron. In this case, as the discharge current grows, for the extra electric current to pass in the cathode region, the increase in the voltage drop therein will not be required, and, at the first approximation, the radiation intensity that determines the current of the electron emission from the cathode will be proportional to this current. But this condition is exactly the condition for the current-voltage characteristic to run vertically – additional quanta required to generate additional electrons are produced by these electrons due to the increase in the energy entering the discharge as the current grows.

According to the experiment during which the electrode was illuminated by the LED light and the maximum current on the current-voltage characteristic was one and a half times as high, photoemission is the main contributor to the electric current from the cathode in the discharge under study. And there are reasons for it. First, due to the reduced work function of the electrodes during cesium adsorption, photoemission covers virtually the entire visible radiation spectrum of the cathode layer. Second, formation of W–Th–Cs structures can significantly increase the work function similarly to the photomultiplier. Third, the cathode layer radiation has an especially spectral structure which is especially beneficial for the photoemission. On the high-field segment, resonance lines of the Xe atom (λ = 119, 125, 130 and 147 nm) must be the first to be excited, since their photon energy is higher than not only the work function of the monoatomic cesium film adsorbed on tungsten (~ 1.7 eV) but also the Cs atom ionization (3.89 eV). In the positive column of the regular glow discharge in xenon, resonance lines carry away about a half of the radiation energy [9]; on the high-field segment of the cathode layer, they must be the first to be excited because their share in its radiation shall be at least the same. Such significant decrease of ϕ_k shall increase the photoemission in this spectrum region drastically. This is the main factor. The combination of the intensive resonance radiation of xenon atoms with the low work function of cesium coatings on the electrodes determines the specific features of the glow discharge in the Xe–Cs mixture. These specific features do not exist separately in xenon or cesium. Finally, the flow of excited Xe atoms to the cathode gives rise to the same emission of electrodes and is equivalent to photoemission.

Photoemission and impact of the natural external illumination can be also the factors that cause the drop of ignition voltage U_{ign} observed in cold lamps. This value was equal to 460 V for burner 11/35 U_{ign}. For it $P_{\text{Xe}}{\cdot}L$ = 70 Torr·cm, it corresponds to U_{ign} = 2000 V on the xenon-specific Paschen curve, which is 4 times is high. For the lamp with burner 5/22, $P_{\text{Xe}}{\cdot}L$ = 45 Torr·cm, with U_{ign} = 1400 V derived from the Paschen curve, which is 3 times as high as 500 V obtained experimentally. Such significant drop of the ignition voltage means that high photoemission factors and presence of even small cesium amounts change the avalanche-type mechanism of breakdown in pure xenon drastically.

From a practical outlook, low ignition and burning voltages of the photoemission discharge make it much easier to design preheating ESE for PPD lamps, while due to relatively high currents the temperature of electrodes shall grow quite fast. The only thing that requires confirmation is that the transition to the arc mode being observed corresponds to the diffuse tie to the electrodes. In this case the cathode sputtering of the electrodes is reduced almost to nothing, because the contribution of the ion-electron emission to the electron current from the cathode, which seems to be very insignificant, while the cathode drop of the voltage is several times lower.

Conclusion

Research of the discharge ignition with cold electrodes in cesium illuminating lamps revealed the unusual “high-current” form of the glow discharge that is formed and burns at considerably lower voltages and at the currents that are 1–2 orders of magnitude higher than that of the regular glow discharge in pure xenon or cesium. Essential characteristics of such high-current glow discharge were obtained, a number of its patterns were established preliminarily. The specific features of a high-current glow discharge in xenon with cesium added are supposed to be caused by the formation of W–Th–Cs film structures on the electrodes with the low work function and high photoemission in relation to the short-wave resonance radiation of xenon atoms in the cathode layer. The high-current glow discharge mode is extremely favourable for designing ESE for cesium PPD preheated lamps, since it prevents erosion-induced cathode spots that shorten the service life of the light source. From the standpoint of both physics of gas discharge and practical significance, further, more detailed, research of the high-current glow discharge in steady-state modes and, first of all, spectroscopic study of the phenomena described herein, is of great interest.

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