Discharge and photo-luminance properties of a parallel plates electron emission lighting device

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Abstract: The gas discharge and photo-luminance properties of a planar lighting source featuring highly uniform light emission and mercury-free design were studied. The current density-voltage characteristics and the associated gas discharge of the devices operating with the values of the ratio of electric field to gas pressure (*E/p*) between 4.3 kV/Torr-cm and 35.7 kV/Torr-cm indicate that the width of the cathode fall extends over the entire gap between the two electrodes and the device is mostly in the obstructed discharge regime. The optical emission analysis confirmed the electron collision-induced gas emissions and strong effect of gas pressure on the phosphor emission when operated at constant current density, both are indicative of the primary roles played by the electron energy.

OCIS codes: (230.0230) Optical devices; (250.0250) Optoelectronics.

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1. Introduction

Recently, flat electron emission lighting device has been proposed as a viable candidate for environment friendly planar light source with highly uniform light emission [1]. The device with its unique structure, nonetheless, is operating under conditions with extremely small *pd* values, where *p* is the gas pressure of nitrogen and *d* is the gap distance between the two

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planar electrodes. Indeed, as indicated previously, the implemented devices which gave rise to reasonable efficacies were mostly operated on the left hand side of the Paschen curve minimum [1]. Although such harsh operation conditions may appear to be a major challenge from the engineering point of view, it is, nevertheless, representing an area that is seldom explored scientifically. For instance, in typical operation conditions with *pd* values in the range of 0.1-0.2 Torr-cm, in addition to a high breakdown voltage on the order of kV range expected from the Paschen's law, the system is highly likely in the state of obstructed discharge [2–5]. The generation of highly-energetic electrons in the current device thus may be described by taking the large ratio of electric field to gas pressure, *E/p*, into account. However, under such circumstances, significant effects of implantation-induced cathode alloying and the resultant reduction of electron emission [6,7] may further complicate the detailed electron emission properties and thus the control of the device operation parameters. Since the lighting of the current flat electron emission lighting device is very much relying on the energetic electrons impinging at the phosphor-coated anode, thus as a light source, the current device is fundamentally different from the existing lighting devices, such as plasma display panel (PDP) and cold cathode fluorescent lamp (CCFL) [8], both operating in the domain of large *pd* values, and from the field emission display which is operating in high vacuum environment. As a result, the correlations between the discharge behaviors and the current-voltage characteristics of the device operating under these extreme conditions are thus of essential importance.

Previously, the current-voltage characteristics and electron energy distribution of nitrogen gas discharge to the left of the Paschen minimum were studied by Yumoto et al. [9,10]. In their studies, it was shown that, in addition to the very high energy for majority of electrons arriving anode, generation of electrons by the collision-induced ionization processes is unlikely to take place in the space near the cathode. This is consistent with the measurements based on optical emission spectroscopy (OES) [1], wherein the intensity of phosphor emissions was found to increase markedly while some spectral lines of nitrogen molecules in the discharge glow diminished gradually as the gas pressure became lower. Since the excitations of gas molecules occur usually only in a certain range of the electron energies [11], thus the OES-observations might also serve as an important complementary tool in unveiling the peculiar behavior of electrons prevailing in these extreme operation conditions and help to elucidate the details of lighting mechanism. In this work, systematic investigations on the correlations between the photo-luminance (both from the discharged N_2 gas and anode phosphors) and current-voltage characteristics are carried out to give a detailed account for the devices operating at an *E/p* value as high as 40 kV/cm-Torr, or 120 kTd.

2. Experimental details

The experimental set-up used in this study was largely similar to those described in the previous work [1]. Briefly, the basic structure of the device consists of a cathode glass plate, a glass spacer, and an anode glass plate. Both electrode glass plates are coated with a transparent and electric conducting film of fluorine-doped tin-oxide (FTO) on their inner surfaces. The thickness of the glass spacer is 10 mm, such that the gap between the two conductive electrodes is d = 10 mm. We used the nitrogen gas with purity of 99.99% as the working gas filling inside the space between the two electrodes. The pressure of the nitrogen gas was monitored by a vacuum gauge attached to a pumping system and was kept at a certain constant value during the whole course of measurement. A layer of cathodoluminance (CL) phosphor, LDP-G1 from Kasei Co., was coated on the conductive surface of the anode and served as lighting screen with an area of 30 x 30 mm^2. The dc voltage power (Keithly 248) and picoammeter (Keithly 6485) were used for analyzing the current-voltage characteristics in various discharge states. The phosphor layer on the anode was found to result in an increase of breakdown voltage V_b by nearly 1 kV. This modifiation in V_b is believed to result primarily from the charging effect of phosphor [12], which remains as another important subject to be resolved in the near future. Mutifunction color analyzer (Ruyico Tech.) was used as the luminance meter to detect the intensity of the various emissions. The conversion between the

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measure luminance and the device efficacy formally obtained using the integrated sphere the methods practiced in Ref [13]. were adopted. The OES probe (StekkarNet EPP200V) was positioned on the top of the device to reveal the emissions from the gas and phorsphors. Due to the resolution limitation and shallow electrode spacing (1 cm) of the current device, we were unable to resolve the spatial distribution of the gas emissions.

3. Results and discussions

Figure 1a shows the typical current density-voltage (*V-J*) characteristics of the present devices obtained with P_{N2} = 0.11 Torr (o), P_{N2} = 0.13 Torr (●), and P_{N2} = 0.21 Torr (□), respectively. It is immediately clear that each *V-J* characteristic of these devices can be roughly divided into three distinctive regions, namely the nearly constant current region prior to breakdown, the "breakdown" region featuring sudden increase in current with nearly constant voltage, and the high current range (J > 10^{-2}-10^{-1} A/cm^2) with rising voltages. The first region, with the current density ranging from 10^{-6} to 10^{-5} A/m^2, is presumably originated from the background ionizations [2,3]. It is noted, however, that, in the present case, the current density of this region is much higher than the usual gas discharge behavior operated with 2 < *pd* < 20 Torr-cm [2]. Furthermore, the nearly flat *V-J* characteristic displayed in the second region, although may be attributed to either the Townsend discharge or normal glow discharge behaviors observed in usual gas discharge with parallel plate electrodes, is more likely a combined exhibition of both in current operation conditions. That is, owing to the extremely small *pd* values of the present devices, there is no apparent transition from Townsend to normal glow. It is, nevertheless, very interesting to note that a portion of *V-J* curve akin to positive Townsend discharge appears to grow with reducing *pd* value. As a result, the breakdown not only occurs at higher device voltages but also at larger current densities, as indicated by the arrows shown in Fig. 1a. This portion of the *V-J* characteristic is, to some extent, also qualitatively similar to that of the cathode-fall dominated discharges [4,5]. The cathode-fall in gas discharge is characterized by a dark zone in front of the cathode. The thickness of the cathode-fall region d_k can be estimated by using the following expression

$$J / p^2 = 2\varepsilon_o V_k v_i (1+\gamma_{app}) / (pd_k)^2,$$

with V_k being the cathode-fall voltage, v_i being the ion velocity and γ_{app} being the apparent secondary emission coefficient of the cathode material [4,5]. For the discharges taking place in our devices with *pd* < 0.2 Torr-cm and by assuming V_k being approximately equal to 1 kV, it is found from simple calculation that $d_k > d$, where d = 1 cm is the distance between the two electrodes. Since the thickness of the cathode-fall evidently extends from the cathode to the anode in all of our cases, the electric field *E* can be considered as nearly spatially uniform. Finally, the region where the voltage appears to be increasing again with further increase in current density may be regarded as the transition into the abnormal discharge. The behavior exhibited in this regime, nonetheless, is very much dependent on the actual operating gas pressures. Hence, further investigations are needed to verify the discharge mode in occurring in this regime.

Figure 1b shows the phosphor emissions or photo-luminance as a function of current density (*L-J*) for the corresponding devices shown in Fig. 1a. In general, the photo-luminance was observed and measured only after gas breakdown, since then the current density increased significantly to excite and render the phosphor emissions detectable. We note that, although the *V-J* characteristics suggest the system may have been into the obstructed discharge regime and the effects of electron backscattering from the anode would play some role in usual discharge device, it is in fact advantageous for the present device configuration. Namely, all the electrons arriving anode would contribute to the photo-emission from the phosphor coated on anode. As is evident from Figs. 1a and 1b, there exists a correlation between the device voltage and the photo-luminance as the current density varies from 10^{-3} to 10^{-1} A/m^2. The photo-luminance appears to be enhanced at lower gas pressures. We will try to understand this pressure effect with the aids of the OES measurements described below.

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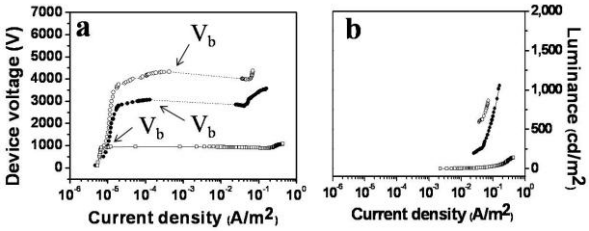

Fig. 1. (a) The current density-voltage characteristics of devices operated at various gas pressures. (○, p = 0.110 Torr; ●, p = 0.130 Torr; □, p = 0.210 Torr); (b) Photo-luminance versus current density (L-J)for the corresponding devices shown in (a).

The OES technique is based on the assumption that spectral emissions are closely relevant to electron energy, such that only those electrons possessing specific energies can excite effectively the corresponding energy level transitions in gas atoms or molecules through collisions. In other words, the emergence and the intensity of the specific spectral lines may reveal information about the energy state of electrons as well as the number of electrons at these specific energy states. Figure 2 shows the OES spectra obtained from a device operating at a gas pressure of 0.210 Torr, corresponding situation of E/p < 10 kV/Torr-cm, measured with discharge current density of 0.086 A/cm^2, 0.173 A/cm^2, and 0.268 A/cm^2, respectively. As can be seen from the results, in addition to the main emission peaked at 530 nm from the anode phosphors, there are three emission peaks from the gas emission. The emission at 391.5 and 427.5 nm are associated with the first negative emission of N_2^+ excitations, while the 357.5 nm peak with barely discernible intensity is associated with the second positive emission of N_2 [11]. The appearance of these specific emission peaks can be explained by the electron energy dependences of the excitation coefficients for the energy levels of N_2 and N_2^+, respectively. Thus, the electron energy associated with the operation condition of 4.3 kV/Torr-cm (13 kTd) probably does give rise to effective excitation cross section for N_2 species [11]. The inset of Fig. 2 further shows the measured emission intensity as a function of current density of light emissions at different current densities. The nearly linear dependence between the emission intensity and device current density for the 391.5, and 427.5 nm gas peaks indicates that the predominant emission mechanism is indeed due to electron collisions. The somewhat deviation from the linear behavior for the 530.0 nm peak is presumably due to complicated electron-induced photoemission characteristics inherent to phosphors materials.

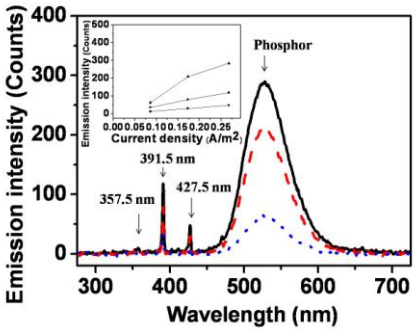

Fig. 2. (Color online) Optical emission spectrum of device operated at a nitrogen pressure of 0.21 Torr (E/p < 10 kV/Torr-cm) with current densities of 0.086 A/m^2 (blue dot line), 0.173 A/m^2 (red dash line), and 0.268 A/m^2 (black solid line), respectively. The inset shows the variations of the emission intensity with current density for 391.5 nm, 427.5 nm, and 530.0 nm emission lines, respectively.

At higher E/p values (lower gas pressures), however, the emission exhibits very different behaviors from those described above. Figure 3 shows the spectral emission intensity obtained at a fixed current density of 0.086 A/m^2 while varies the operation gas pressure from 0.210

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Torr (E/p < 10 kV/Torr-cm) to 0.110 Torr (E/p > 30 kV/Torr-cm). It is immediately clear that the phosphor emission peaks around 530.0 nm grows remarkably with reducing gas pressure. On the contrary, the intensity of the spectral line at 391.5 nm diminishes with decreasing gas pressure, as highlighted in the inset of Fig. 3. Since in this case the E/p value increases from 4.3 kV/Torr-cm (E/n = 13 kTd; 1Td ≡ 10^{-21} Vm^2) for p = 0.210 Torr to 35.7 kV/Torr-cm (E/n = 110 kTd) for 0.11 Torr, thus by assuming a uniform electric field E across the gap between the two electrodes, the diminishing of the emission intensity of the 391.5 nm line may merely reflect the fact the electron energy has become too large to give optimum excitation coefficients for relevant energy levels [11]. Within the context of this scenario, the marked growth of the intensity of the 530.0 nm peak may be similarly interpreted as a result of the increase of electron energy when the gas pressure is reduced, while the electron number remains approximately constant. This can also explain the drastically enhancement of current density-dependent luminance for lower pressure cases, as displayed in Fig. 1b.

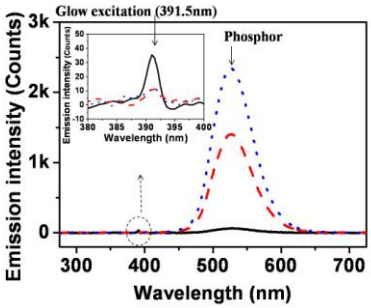

Fig. 3. (Color online) Optical emission spectra for devices operated with various gas pressures at a constant current density of 0.086 A/m^2. The blue (dot line), red (dash line), and black (solid line) curves are for pressure of 0.110Torr (30 kV/Torr-cm < E/p), 0.130 Torr (20 kV/Torr-cm < E/p < 30 kV/Torr-cm), and 0.210 Torr (E/p <10kV/Torr-cm), respectively. The inset shows an enlarged portion ranging from 380 nm to 400 nm.

Next, we turn to discuss the lighting properties for the current devices. Figure 4 shows the photo-luminance characteristics of devices operated at various pressures as a function of the input electric power. Again, it illustrates the quasi-linear behavior and is indicative that the electron energy may have been playing the key role in the overall luminance. This is not surprising considering that the predominant luminance is coming from the phosphors coated on the anode. In the inset of Fig. 4, we plot the photo-luminance as a function of operating gas pressure at a constant electric input power of 0.2 W. It appears that there exists an optimum range of gas pressure for obtaining maximum efficacy in the current devices. The lighting efficacy of the device configuration can be evaluated by using the expression

$$K = \frac{\pi L A}{P_E},$$

where K is the lighting efficacy, L is the luminance, A is the top area of the transparent anode and P_E is the electric input power [13]. From the measured data displayed in Fig. 4, the lighting efficacy is around 8 - 10 Lm/W for devices with A = 30 x 30 mm^2. An enhancement up to 25-30 Lm/W was observed in a device of the same size 30 x 30 mm^2 in which cathode material with high secondary electron coefficient was used. It is anticipated that by further investigations in searching for proper cathode and phosphors materials the gas breakdown, discharge behaviors, and eventually the lighting efficacy of the current devices can be further improved [3–6].

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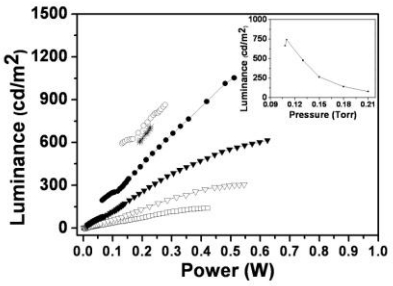

Fig. 4. The input power dependence of the photo-luminance obtained for a wider range of gas pressures.(X, p = 0.108 Torr; ○, p = 0.110 Torr; ●, p = 0.130 Torr; ▼, p = 0.150 Torr;▽, p = 0.150 Torr; □, p = 0.210 Torr). The inset shows the variation of the luminance with the gas pressure at a constant input power of 0.21 W.

4. Conclusions

In summary, the current density-voltage characteristics and the associated gas discharge as well as the photo-emission properties were reported for a potential lighting device with narrow gap planar parallel electrodes. This lighting device was operated under relatively small *pd*-values such that the breakdown voltage of the gas discharge was located on the left-hand side of the Paschen curve minimum. Under these conditions, the discharge characteristics appeared to be in the obstructed discharge regime. Analysis based on optical emission spectroscopy was made to elucidate the role of electron energy and electron number involved in exciting the optical emissions from both the working gas and the phosphor material coated on the anode. The results indicated that the lighting properties were dominated by the ratio of electric field to gas pressure. Preliminary results have indicated that the luminance efficacy of the current device may be significantly improved by replacing the cathode with materials having higher secondary electron emission coefficients. Intensive investigations along this direction as well as in selecting appropriate phosphor materials will prove beneficial in developing this type of environmentally sustainable lighting devices.

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