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RESEARCH ARTICLE

Transient and stable electroluminescence properties of alternating-current biased organic light-emitting diodes

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Abstract In this work, transient electroluminescence (EL) (brightness-voltage waveform curve) was utilized to investigate the working mechanism of alternating-current biased organic light-emitting diodes (AC-OLEDs). In lower frequency domain, injection potential barrier was the dominant effect to determine the luminescence intensity; with increased frequency, the influence of capacitance effect becomes dominant, which can be confirmed according to the investigations on stable EL of the AC-OLEDs. The results indicate that transient and stable EL can agree with each other perfectly. Besides, the stable EL reveals that the thinner device can take more effective capacitance effect.`

Keywords organic light-emitting diodes (OLEDs), alternating-current (AC), transient electroluminescence (EL)

1 Introduction

In recent years, organic light-emitting diodes (OLEDs) have attracted more attention because of their high luminescence efficiency, low operating voltage, variety of emission color and potential applications in flat-panel displays, a lot of efforts are focused on studying luminescence mechanism, material synthesis and device configurations in order to realize the fine properties of OLEDs [1–5].

OLEDs are generally operated in direct-current (DC) mode, however, some obvious drawbacks greatly hinder the OLEDs in this DC mode of the applications, and dramatically reduce the performance of device, which can be ascribed to these three aspects: (1) space charges formed under DC bias and the weakened efficient electric field in the bulk; (2) the accumulated redox effect; (3) quenching centers caused by the transfer of the metal atom to the organic layer in electrode [6,7].

Great efforts were made to overcome these problems and the way with alternating-current (AC) bias was proved to be an effective one, which can dramatically improve the stability and lifetime of the OLEDs. Herein, the alternating-current organic light-emitting diodes (AC-OLEDs) have attracted much attention for their unique operation mode and advantages [8–13]. However, some obstacles, such as the effect of frequency and capacitance effect on the AC-OLEDs, still exist, and further study is necessary. In this paper, according to systematically study the transient and stable electroluminescence (EL) in different frequency domain, the effect of frequency and capacitance effect on AC-OLEDs was studied. The results indicate that the injection potential barrier and the apacitance effect will become dominant in the low and high frequency, respectively; and the thinner device can take more effective capacitance effect.

2 Experimental

We fabricated the two types of OLEDs: (A) ITO/Alq_3 (Tris-(8-quinolinolato)aluminum)(80 nm)/Al and (B) ITO/Alq_3 (40 nm)/Al. The ITO glass substrates (50 Ω/sq) with transmissivity 85% were rinsed with ultrasonic bath in acetone, ethanol and de-ionized water in sequence. The Alq_3 (purchased from Alfa Aesar with the purity of 99.9%) was prepared in a vacuum chamber (the pressure was 2×10^{-6} Torr) by thermal evaporation method. The typical deposition rate was about 0.03 nm/s. The thickness of layer is controlled by a quartz crystal monitor. The top Al electrode was prepared by thermal evaporation also. The size of the devices is 2 cm × 2 cm, and the area of the electrode deposition on the devices is 2×10^{-5} m^2. The schematic diagram of the OLED, the energy level diagram of the device and the chemical structure of Alq_3 are shown

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in Figs. 1(a)–1(c), respectively. The stable EL spectra were measured by Spex Fluorolg-3 spectrophotometer. The brightness-voltage waveform curves were obtained by oscillograph (Tektronix TDS 540D). All measurements were performed at room temperature under ambient condition.

3 Results and discussion

Transient EL of device A is investigated using brightness-voltage waveform curves under sinusoidal AC voltage 24 V at different frequencies, and it is shown in Fig. 2. In our experiment, the ITO and Al are connected with negative and positive electrode, respectively. In the lower frequency domain, we can see that EL peak in one cycle is detectable in negative direction and no luminescence can be observed in positive direction, as shown in Figs. 2(a) and 2(b). To our knowledge, the luminescent manner of the device is injection luminescence, and the potential barriers are the dominant factor in determining the luminescence, so the luminescence intensity driven by forward and reverse voltage is different because of the existence of the injection barrier. Under the negative direction of a cycle, the holes and electrons can inject efficiently from ITO and Al respectively, so the luminescence can be obtained. Under the positive direction of a cycle, the EL intensity is not detectable because the injection barrier is much higher compared with positive direction. It can be seen from the energy level diagram of the devices (Fig. 1(b)). In the negative direction, there is a 1.1 and 1.2 eV injection potential barrier for electron and hole, respectively. On the contrary, in the positive direction, the injection potential barrier for electron and hole are increased to 1.6 and 1.7 eV, respectively. According to the Fowler-Nordheim equation, the influence of barrier potential on injection of carrier can be estimated by [14]:

$$J_{\mathrm{t}} \propto \exp\left[-\frac{8\pi(2m^*)^{\frac{1}{2}}\phi^{\frac{3}{2}}}{3hqE}\right],$$

J_{t} is the tunneling current, h is the Plank constant, E is the electric field, ϕ is the zero field barrier height, m^* is the effective mass of the carrier, q is the electron charge.

From Figs. 2(a) and 2(b), it can be seen that the EL intensity increases with increased frequency. The relationship between the intensity and frequency can be interpreted as a result of more holes and electrons injection and recombining if more AC voltage cycles are accomplished within a fixed time interval.

With increased frequencies (from Figs. 2(d) and 2(e)), as we can see, the EL emission wave curves change dramatically, when the frequency is 200000 Hz (as shown in Fig. 2(e)), it almost becomes a straight line,

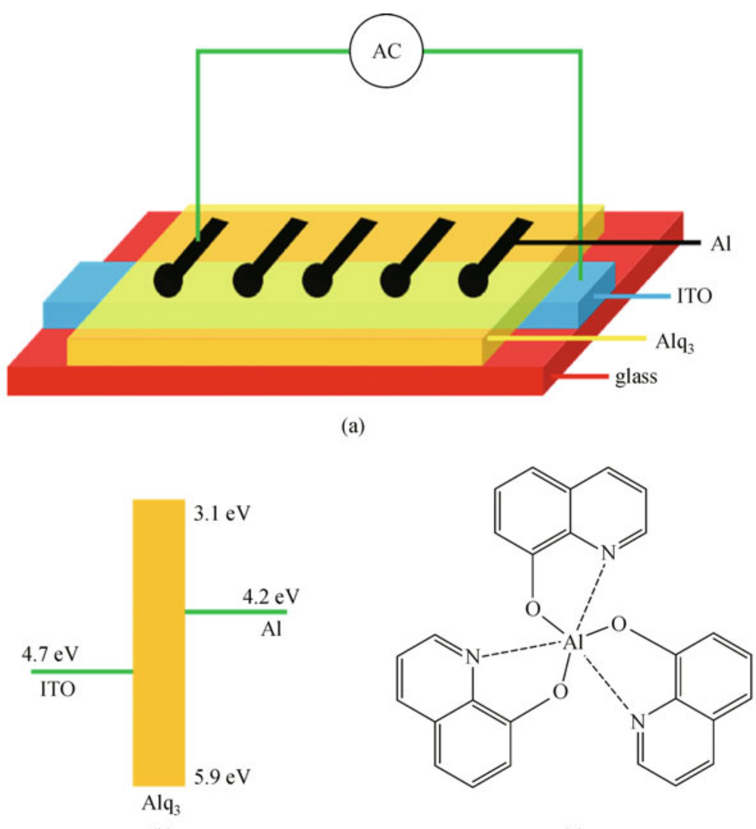


Fig. 1 (a) Schematic diagram of OLED; (b) energy level diagram of devices; (c) chemical structure of Alq_3

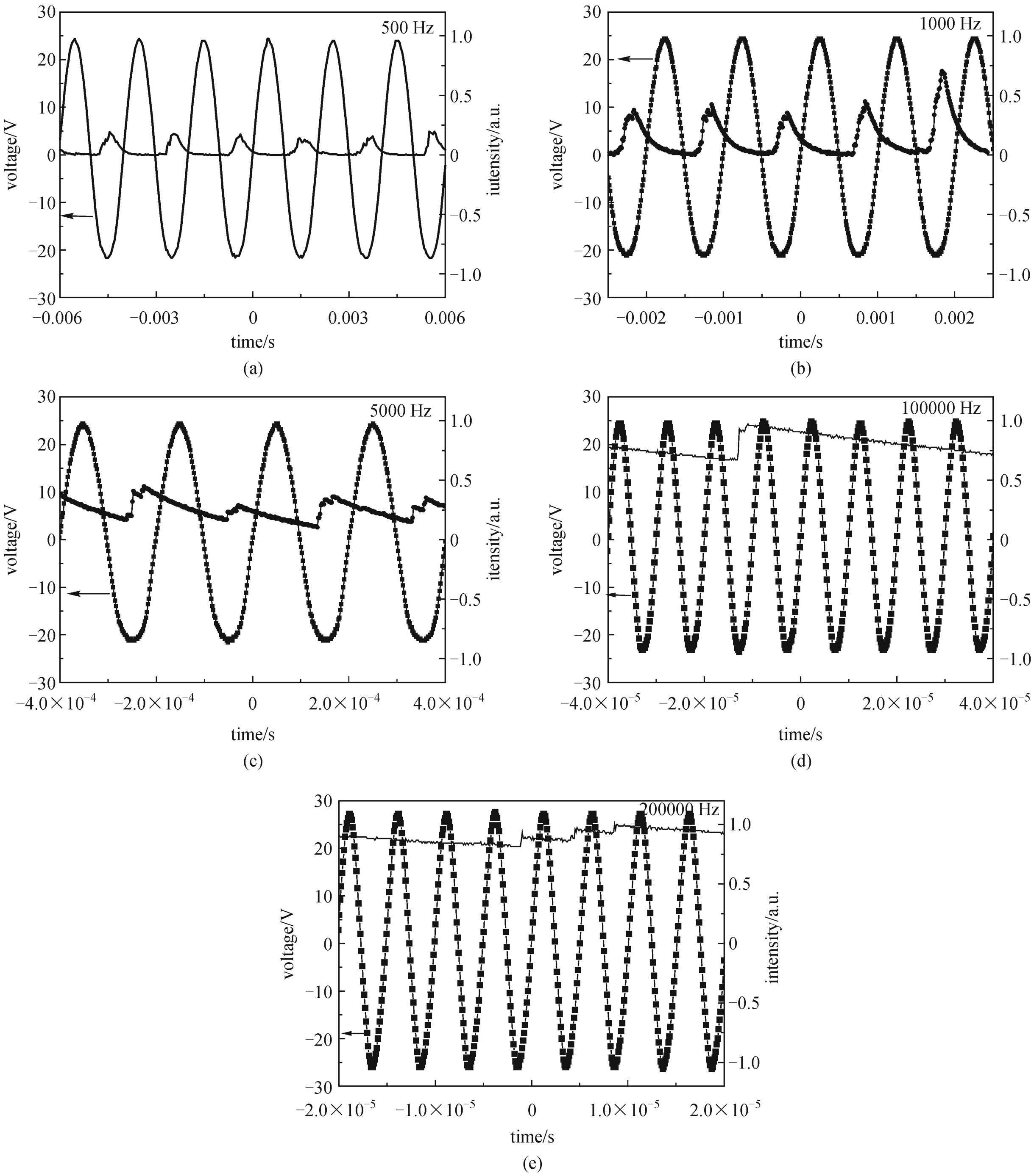


Fig. 2 Brightness-voltage waveform curves under AC voltage at different frequencies: (a) 500 Hz; (b) 1000 Hz; (c) 5000 Hz; (d) 100000 Hz; (e) 200000 Hz

and the potential barrier is not the dominant effect to determine the luminescence intensity in different directions. We attribute these phenomena to the influence of the capacitance effect, the phenomenon of which can be defined as that the electric field in the capacitor is increased with increased frequency. According to our previous work [15], the OLED can be modeled as resistance (R_p) and capacitance (C_p) in parallel and with a series resistance (R_s), and the equivalent circuit of the device is shown in the Fig. 3. The higher electric field can make effective carrier injection, so the luminescence can be detected in both directions, and the intensity is increased with increased frequency.

To identify the influence of frequency and capacitance effect on the EL properties, the stable EL studied. Figure 4 shows the stable EL spectra of the device A. The applied

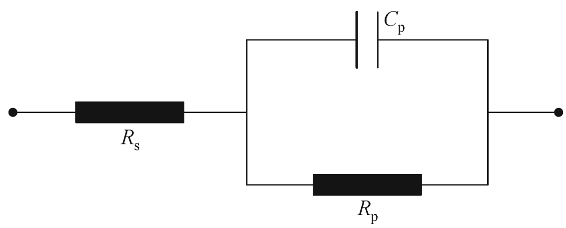
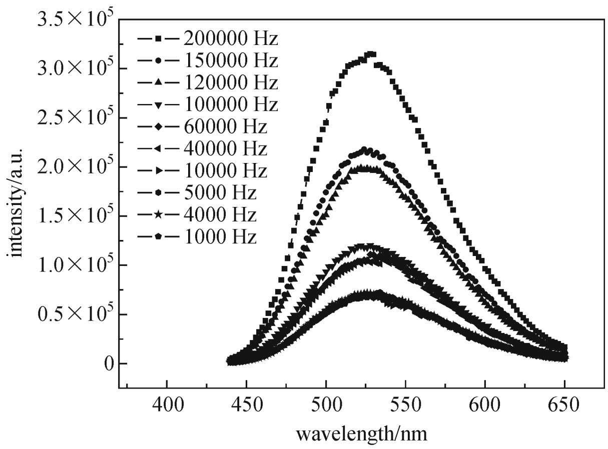
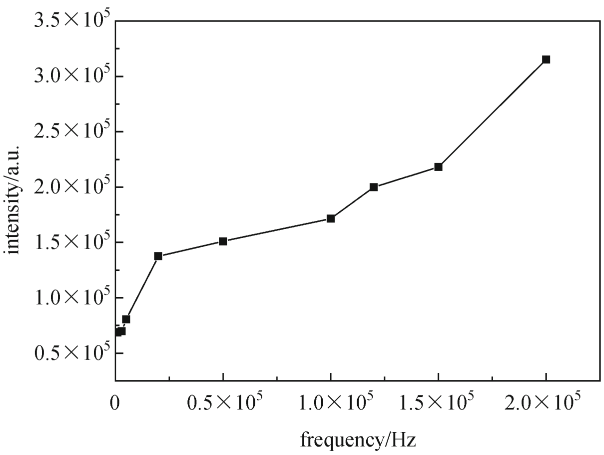


Fig. 3 Equivalent circuit of OLED

voltage is 24 V for the whole series of experiments while the frequency is varied. In our measurement scope (the maximum frequency is 200000 Hz), the intensity increases dramatically with increased frequency. The results agree with the transient EL results. Figure 5 shows the stable EL spectra of the device B. The applied voltage is 8 V for the whole series of experiments while the frequency is varied. The intensity increases dramatically with increased frequency. For a further increase in frequency, a decrease in intensity is obtained.

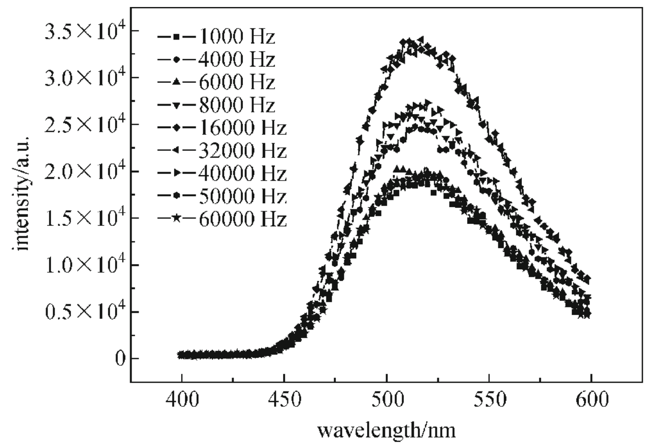


(a)

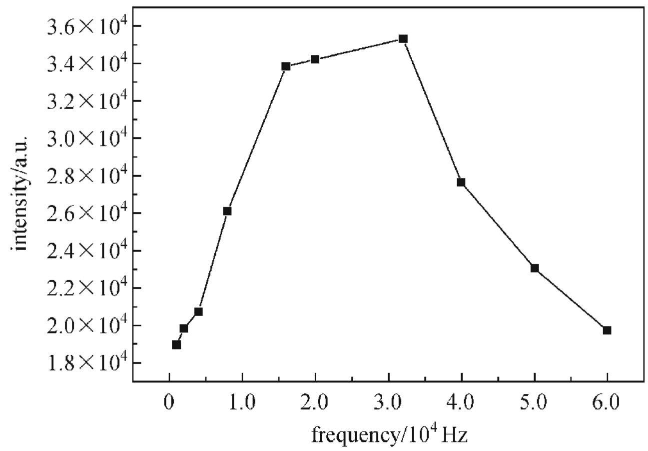


(b)

Fig. 4 (a) Stable EL spectrum of device A; (b) frequency response of stable EL intensity of device A



(a)



(b)

Fig. 5 (a) Stable EL spectrum of device B; (b) frequency response of stable EL intensity of device B

For device A, the increased luminescence intensity can be interpreted as: (1) more holes and electrons injection and recombining after more AC voltage cycles are accomplished within a fixed time interval; (2) in the higher frequency domain, the capacitance effect makes the electric field increased, and the luminescence can be obtained in both direction. So the luminescence intensity is increased further. For device B, the cause in increased intensity domain can be interpreted by the two items mentioned above. The decrease may be induced by the device degradation under higher electric field caused from capacitance effect. Compared it with the device A, the device A is thinner (the capacitance higher, the capacitance effect more effective), and it does not suffer from higher electric field. So the device is degenerated, the luminescence intensity is decreased. Besides, under such high electric field, some of the carriers are swept to the counter electrode without recombination [15].

In the low frequency domain, the frequency is the dominant factor in determining luminescent intensity, and with the increased frequency the EL intensity is increased.

In the high frequency domain, the effect of capacitance effect becomes more notable which can make the EL increase also. However, higher electric field caused from capacitance effect can make device degrade. Especially, the thinner device which has higher capacitance and effective capacitance effect can degrade first under the same frequency. In our two sets of devices, device B reaches the maximum intensity first with increased frequency. So, we can conclude that thinner device may take more effective capacitance effect. Research in this work on special OLED can give some important clues to study the transient and stable EL properties of AC biased OLED, and it will be inevitably beneficial to improve the luminescence efficiency of OLED.

4 Conclusions

In summary, the luminescent mechanism of AC biased OLEDs is injection luminescence and the potential barriers are the dominant factor in determining the luminescence in the lower frequency domain. In the high frequency domain, the effect of capacitance effect becomes more notable which can make the EL in both directions, and the effect of potential barrier can be neglected. The mentioned conclusions can be identified by the stable EL. Besides, we indicate that the thinner device is more sensitive to the capacitance effect.

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