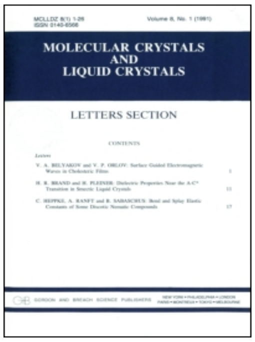

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Frequency-dependent response of organic light-emitting diodes driven by DC and AC voltages

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ABSTRACT

In order to understand electrical and optical properties of the organic light-emitting diodes (OLEDs) driven by DC and AC voltages, characteristic frequency and *RC* equivalent circuit were investigated from the frequency-dependent response of the device. Luminance of the DC + AC driven OLED is less affected by frequency and waveforms (sine and square) of the AC voltage, and it is similar to that of the DC driven OLED. Unlike the AC driven OLEDs, the DC + AC driven OLEDs maintain the electroluminescent characteristics of the DC driven OLEDs. At low frequency of 40 Hz, a real part of impedance (Z') above a turn-on voltage decreases exponentially with increasing voltage. Its behavior shows a similar pattern to a current flow of the DC driven OLEDs. As the frequency increases, a magnitude of resistive component (R_p) decreases and that of capacitive effect drastically increases. As the applied voltage increases, characteristic frequency exponentially increases. Application of the AC voltage with a proper frequency lower than the characteristic frequency to the device may reduce the accumulation of charge in the capacitive component (C_p) of *RC* equivalent circuit. Since this operation reduces a formation of space charge, it is expected to facilitate the charge transport.

KEYWORDS

DC and AC; frequency-dependent response; impedance; space charge; RC equivalent circuit

Introduction

Since the organic light-emitting diodes (OLEDs) have a potential application as a next-generation display, they are getting attention during the last several decades [1]. In general, the operating mechanism of the OLEDs is in a sequence of injection of charge carriers, transport, recombination of hole-electron, and radiative emission. In carrier transport process of the OLEDs, unlike the band conduction of inorganic materials, dominant transport process in amorphous organic materials is hopping conduction. Thus, the organic material, in general, has a lower mobility than that of metal used as an electrode. For this reason, charges are accumulated at metal-organic interface.

Since the mobilities of hole and electron are different in organics, it is not easy to adjust the charge balance. The mobility difference of these charge carriers increases the

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accumulation of charges in bulk and at the organic-organic interface, and then it causes a space-charge formation. The formed space charge generates a small electric field opposite to a direction of the applied voltage, and it interrupts the injection of charge carriers. It is one of the reasons degrading the device. Thus, it is necessary to study on the electrical transport process in organic materials and charge distribution inside the device [2–5].

In order to decrease the degradation of the device, many researchers have been studying the AC driven OLEDs. Since the AC voltage periodically changes a direction of the electric field, it can reduce the space-charge formation. As a result, stability and lifetime of the device could be improved [7]. However, since the recombination rate decreases with increasing frequency, electroluminescence is weakened. Applied electric field to the device can be modified by applying the DC + AC voltage [8,9]. This operating method is expected to reduce the space charge and to maintain the electroluminescent characteristics of the DC driven device.

Since the impedance analysis method uses the DC + AC signal, it is suitable to observe the electrical properties of the device [2–6]. And the impedance analysis is useful in analyzing the *RC* equivalent circuits of the device [2,3,11]. Kim et al. studied on the conduction mechanism of the OLEDs using the *RC* equivalent circuit [11]. Recently, Zhang et al. observed the space charge distribution and recombination process through the capacitance–voltage (C–V) characteristics using the impedance spectroscopy [12].

In this study, we have investigated the frequency-dependent response of the OLEDs driven by DC and AC voltages. And we have focused on the electrical properties, charge injection and transport, and *RC* equivalent circuit of the OLEDs.

Experimental

Manufactured device structure is ITO(180 nm)/TPD(40 nm)/Alq_3(60 nm)/Liq(2 nm)/Al (100 nm) as shown in the inset of Fig. 2. Indium-tin-oxide (ITO) substrate used as the anode has a thickness of 180 nm and a sheet resistance of 10 Ω/□. Patterned ITO was cleaned by using SC-1 (hydrogen peroxide:ammonia:deionized water = 1:1:5 mixed solution), acetone, ethyl alcohol, and deionized water in sequence. And organic materials of N,N'-diphenyl-N,N'-di(m-tolyl)-benzidine (TPD), tris(8-quinolinolato) aluminium (Alq_3), and lithium quinolate (Liq) were thermally deposited on the cleaned ITO glass in sequence. The TPD and Alq_3 were used as a hole-transport layer, electron-transport and emissive layer, respectively. And the Liq was used as an electron-injection layer. The TPD and Alq_3 were deposited at a rate of 0.5 $\sim$ 1.0 Å/s, and the Liq was deposited at a rate of 0.1 $\sim$ 0.2 Å/s. The deposited thicknesses of TPD, Alq_3, and Liq were 40 nm, 60 nm, and 2 nm, respectively. After the deposition of the organic materials, aluminium (Al) was deposited to a thickness of 100 nm for cathode. All the evaporation process was performed under a pressure of 1×10^{-5} torr, and the emission area was 3×5 mm^2.

In order to apply the DC + AC voltage to the device, summing amplifier was manufactured using OP-AMP. Schematic of the experimental measurement is shown in Fig. 1. Keithley 236 source-measure unit and function generator (Protek G305) were connected to the summing amplifier in order to supply the DC + AC voltage. And then the combined voltage was applied to the device. The applied DC voltage range and the amplitude of AC voltage were 0 $\sim$ 9 V and 200 mV, respectively. Applied frequency range was 50 Hz $\sim$ 50 kHz, and waveforms were sine and square waves. Si-photodetector and Keithley 617 electrometer were used to observe the electroluminescent characteristics. Impedance analyzer (Agilent 4294A) was used to observe the impedance spectroscopy and the characteristic frequency of the device driven by DC +

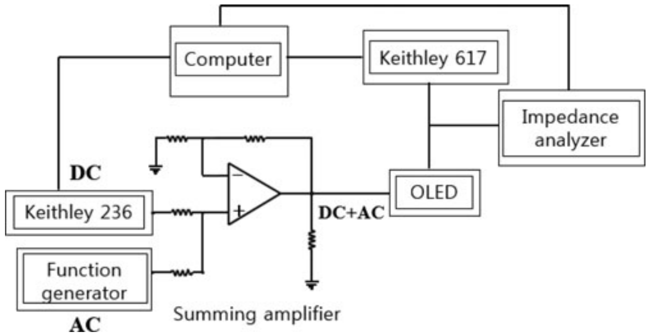

Figure 1. Schematic of the experimental measurements.

AC voltage. The applied DC voltage range was 0 ∼ 8 V. Frequency range and amplitude of AC voltage were 40 ∼ 100 kHz and 500 mV, respectively.

Results and discussion

Figure 2 shows the current density-voltage characteristics of the DC driven OLEDs and the frequency-dependent luminance-voltage characteristics of the device. And it was compared with the luminance of the DC driven device. The frequency range and the AC amplitude are 50 Hz ∼ 50 kHz and 200 mV, respectively. The applied waveforms are sine and square waves. The luminance of the device is almost not only independent on the waveforms but also on the frequencies. Thus, unlike the AC driven OLEDs, the DC + AC driven OLEDs can maintain similar electroluminescent characteristics to those of the DC driven OLEDs.

Electrical properties and frequency-dependent response of the OLEDs driven by DC + AC voltages can be investigated using the impedance analyzer. Figure 3 shows the *RC* equivalent circuit of the device. Complex impedance of the device can be represented by real (Z') and imaginary (Z'') components. Then the impedance of the equivalent circuit of the device can be expressed as follows.

$$Z = Z' - jZ'' = R_s + \frac{R_p}{1 + j\omega\tau} \quad (1)$$

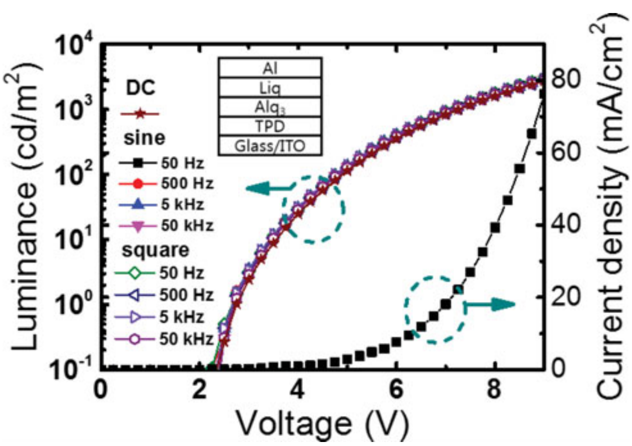

Figure 2. Current density-voltage characteristics of DC driven OLEDs and frequency-dependent luminance-voltage characteristics of DC + AC driven OLEDs and DC driven OLEDs. The inset shows a manufactured device structure.

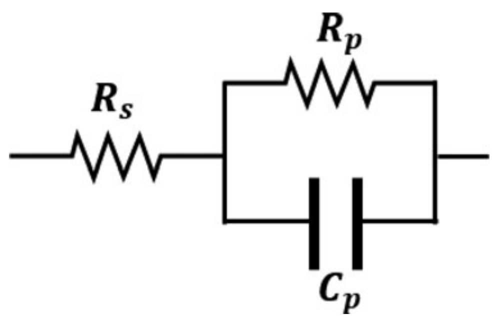

Figure 3. The *RC* equivalent parallel circuit of the OLEDs. R_s is a resistance of electrode, and R_p and C_p are the resistance and capacitance of the parallel circuit.

Here, R_s is the electrode resistance, and $\tau(\tau = R_pC_p)$ indicates a time constant in this equivalent circuit. R_p and C_p are the resistance and capacitance of the *RC* equivalent parallel circuit, respectively. And ω is an angular frequency expressed by $\omega = 2\pi f$. Real part of impedance Z' and characteristic frequency f_c can be expressed as Eqs. (2) and (3).

$$Z' - R_s = \frac{R_p}{1 + (\omega\tau)^2} \tag{2}$$

$$2\pi f_c = 1/\tau = 1/R_pC_p \tag{3}$$

In Eq. (3), the characteristic frequency f_c is given by $f_c = 1/2\pi\tau$. And the real part of impedance at the frequency of f_c is $Z' - R_s = R_p/2$. At this characteristic frequency, there is a crossover of impedance contribution from the resistive to the capacitive effect.

Figure 4 shows the frequency-dependent real part of impedance. The solid lines in the figure are the fitted results using Eq. (2) for the *RC* equivalent circuit. And the characteristic frequencies of the DC + AC driven OLEDs were able to be obtained using Eq. (3). The applied frequency range is 40 Hz $\sim$ 100 kHz, and the resistance of ITO electrode is measured to be about 25 Ω. At low frequency of 40 Hz, a magnitude of real part of impedance drastically decreases above a turn-on voltage of 3 V. It is due to the increased current because of the lowering of resistive component of the device as the applied voltage increases. It is similar to the behavior of current density for the DC driven OLEDs shown in Fig. 2. The characteristic

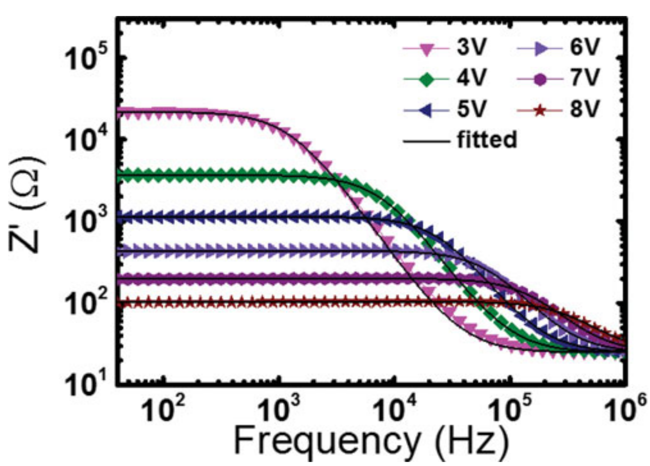

Figure 4. Frequency-dependent real part of impedance of the devices at several DC applied voltages.

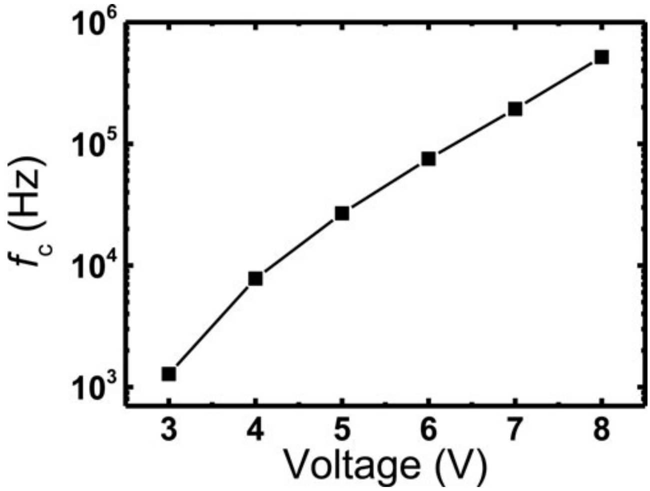

Figure 5. Voltage-dependent characteristic frequency.

frequency f_c at 6 V is 7.5×10^4 Hz. In the frequency range above the characteristic frequency, the resistive effect decreases and the capacitive effect rapidly increases. Since the resistance decreases as the frequency increases, the current in the device increases. Thus, an application of the proper frequency lower than the characteristic frequency may not only reduce the accumulation of space charge in the capacitor of *RC* equivalent circuit, but also facilitate the carrier transport in the device.

Figure 5 shows the voltage-dependent characteristic frequency of the device obtained from Fig. 4. The characteristic frequency increases exponentially with the increase of the applied DC voltage. This phenomenon may appear due to a charge-carrier transit time depending on the electric field.

Conclusion

In this study, we have investigated the frequency-dependent dynamic response of the OLEDs driven by DC and AC voltages. And we have focused on the electrical properties, characteristic frequency, *RC* equivalent circuit of OLEDs. The luminance of the DC + AC driven OLED is less affected by the frequencies and waveforms. And unlike the AC driven OLEDs, DC + AC driven OLEDs maintain the electroluminescent characteristics similar to that of the DC driven OLEDs. The magnitude of real part of impedance drastically decreases above the turn-on voltage of 3 V. And this phenomenon is similar to that of current in the device. When the applied frequency is higher than the characteristic frequency f_c, the magnitude of resistive component decreases and capacitive effect drastically increases. The AC voltage lower than the characteristic frequency may reduce the charge accumulation in the capacitor component of *RC* equivalent circuit. And the application of AC voltage can facilitate the current flow. Thus, it is expected to improve the charge injection and transport properties.

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