Equivalent-circuit Analysis of ITO/Alq_3/Al Organic Light-emitting Diode

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An ITO/Alq_3/Al structure was used to study complex impedance of Alq_3 based organic light-emitting diodes. Equivalent circuit was analyzed in a device structure of ITO/Alq_3/Al with a thickness layer of Alq_3 of 100 nm. The obtained impedance was able to be fitted using equivalent circuit model of parallel combination of resistance R_p and capacitance C_p with a small series resistance of R_s.

Keywords : Complex impedance, Equivalent-circuit model, Resistance, Capacitance, Organic light-emitting diode

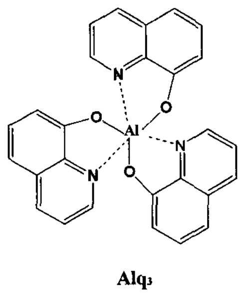
1. INTRODUCTION

Organic light-emitting diode is rapidly commercialized in display market after the first report in 1983 by Tang and Vanslyke. There are currently available other displays such as CRT, LCD, and PDP. However, it is needed having a special function in display due to a development of high-density television and three-dimensional image processing technology.

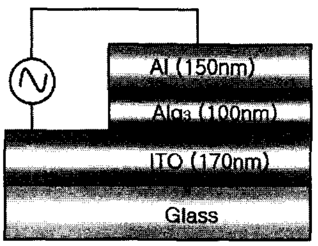
In 1987, Tang and VanSlyke observed green light emission at low voltage using low molecule aromatic diamine and 8-hydroxyquinolinato aluminum (Alq_3)[1]. In 1990, Friend et al., in Cambridge University reported the first green light-emitting polymer diode using poly (phenylenevinylene) (PPV). Since then, lots of progresses have been done to obtain highly efficient and stable light emitting diodes[2-4]. The most suitable display devices which have self-light emitting type, fast response time, low drive voltage, flexible display, large emitting area, high efficiency, and low cost etc. are required[5,6]. To satisfy these conditions, understanding of an electrical conduction mechanism is important in improving the efficiency of the devices[7,8]. In this paper, we report equivalent-circuit analysis in organic light emitting diode through a study of complex impedance depending on voltage and frequency.

2. EXPERIMENTAL

To study an equivalent circuit of the organic light emitting diode, a device structure of ITO/Alq_3/Al was fabricated. Equivalent circuit was analyzed in a device structure of ITO/Alq_3/Al with a thickness layer of Alq_3 of 100 nm. Figure 1(a) is a molecular structure of Alq_3 and Fig. 1(b) is a schematic representation of device structure.



(a) Molecular structure of Alq_3



(b) ITO/Alq_3/Al device structure

Fig. 1. Molecular structure and device structure.

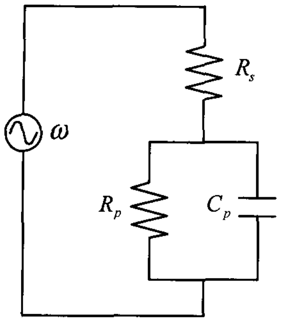


Fig. 2. Equivalent-circuit model of ITO/Alq3/Al device structure.

The ITO(indium-tin-oxide) substrate, which was used as an anode, has a surface resistance of 15 Ω/□ and a thickness of 170 nm. The Alq3 purchased from TCI was thermally evaporated onto the ITO surface at a deposition rate of 0.6~0.8 Å/s under a base pressure of 5×10^{-6} torr. A molecular weight of Alq3 is 459.44 and a chemical formula is $C_{27}H_{18}AlN_3O_3$. An electron mobility of Alq3 is about 5×10^{-5} cm^2/V· s at 10^5 V/cm. A deposition rate of aluminum was 0.5 Å/s up to 20 nm thick, and 10 Å/s in 20~150 nm thickness range. A light-emitting area was 15 mm^2 (5 mm x 3 mm).

A frequency and voltage-dependent response of the device was measured using Agilent 4294A precision Impedance Analyzer at ambient condition.

3. RESULTS AND DISCUSSION

If AC electric field is applied across the organic material, a polarization is formed in a low frequency region as the electric field varies sinusoidally. However, if the applied frequency is higher than the intrinsic vibration of the charged particle that the polarization is caused by, then the polarization is not accomplished very well[9,10].

The voltage-dependent impedance of the device was measured from –5 V to breakdown voltage at four different frequency ; 100 Hz, 1 kHz, 10 kHz, and 100 kHz. And the frequency-dependent impedance was also measured in the frequency range of 40 Hz and 100 MHz by applying discrete bias voltages.

Figure 2 represents the equivalent circuit of ITO/Alq3/Al structure device. The impedance results can be fitted using equivalent circuit model of parallel combination resistance R_p and capacitance C_p with a small series resistance R_s[11-14]. This is illustrated in Fig. 2. Here, R_s is associated with the resistance of the contacts and ITO thin film. However, R_p and C_p can be associated with the AC conductivity and capacitance of the bulk device[12,15,16].

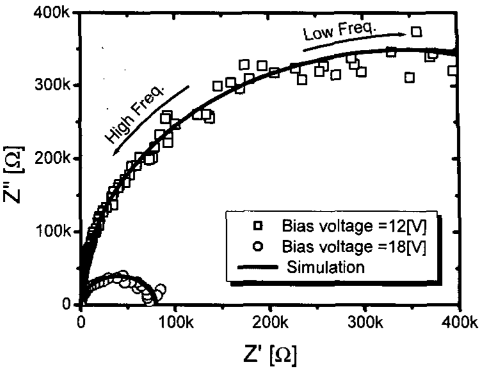


Fig. 3. Variation of the imaginary part of impedance against real part of impedance for a 100 nm.

A complex impedance Z of the equivalent circuit of ITO/Alq3/Al structure device can be expressed in terms of real and imaginary components Z' and Z'' such as

$$Z = Z' - jZ'' = |Z|\,e^{j\theta} \tag{1}$$

Here, $|Z|$ and θ are a magnitude and phase of the impedance, respectively. The phase θ means a phase difference between the applied AC voltage and the AC current flowing through the device. For instance, a phase difference of 0 ° and -90 ° indicates that the device gives a resistive and capacitance response to the applied AC voltage, respectively.

Figure 3 is called Cole-Cole plot. Solid lines in Fig. 3 are simulated ones. Radius of the arc is higher at lower bias voltage. These semicircles can be described by the equivalent circuit proposed in Fig. 2. One single R_pC_p component with a resistance R_s and a constant capacitance C_p is sufficient[13].

In Figs. 2 and 3, the Z' and Z'' can be expressed in terms of R_s, R_p, and C_p such as,

$$\begin{aligned} Z &= R_s + \frac{1}{\dfrac{1}{R_p} + j\omega C_p} \\ &= [R_s + \frac{R_p}{1+(\omega\tau)^2}] - j[\frac{\omega\tau R_p}{1+(\omega\tau)^2}] = Z' - jZ'' \end{aligned} \tag{2}$$

$$Z' = [R_s + \frac{R_p}{1+(\omega\tau)^2}] \quad , \quad Z'' = [\frac{\omega\tau R_p}{1+(\omega\tau)^2}] \tag{3}$$

, where $\tau = R_pC_p$. If the frequency ω varies from 0 to ∞, then Eq. (3) is expressed as follows for certain specific frequencies.

$$\begin{aligned} &\omega=0, && Z'=R_s+R_p, && Z''=0 \\ &\omega\tau=1, && Z'=R_s+\frac{R_p}{2}, && Z''=\frac{R_p}{2} \\ &\omega=\infty, && Z'=R_s, && Z''=0 \end{aligned} \tag{4}$$

Magnitude of impedance |Z| and phase θ in Eq. (1) are estimated such as

$$|Z|=\sqrt{[R_s+\frac{R_p}{1+(\omega\tau)^2}]^2+[\frac{\omega\tau R_p}{1+(\omega\tau)^2}]^2} \tag{5}$$

$$\theta=\tan^{-1}(\frac{Z''}{Z'}) \tag{6}$$

Figure 3 shows the relations between impedance and frequency. Real part of impedance approaches maximum value in low frequency region and minimum value in high frequency region. Imaginary part of impedance approaches minimum value in low and high frequency region, but maximum value in frequency region of $\omega\tau=1$ [9]. Therefore, the maximum absolute value of imaginary part of impedance at $\omega\tau=1$ is a half maximum value of real part of impedance.

Figure 3 can be described by a circular equation. Here, a circular equation is as follows.

$$[Z'-(R_s+\frac{R_p}{2})]^2+[Z'']^2=[\frac{R_p}{2}]^2 \tag{7}$$

In *Z'*-*Z''* plane, this is an equation of circle, having a center at ($R_s+\frac{R_p}{2}$, 0) with a radius of $\frac{R_p}{2}$. The solid lines in Fig. 3 are fitted ones using Eq. (7). From this analysis, it gives a contact resistance of R_s about 25 Ω . And the radius gives a resistance around 698.2 kΩ and 72.9 kΩ for 12 V and 18 V, respectively. The contact resistance comes mainly from the ITO anode and partially from the cathode and a junction between the electrode and organic layer.

When we plot an impedance in *Z'*-*Z''* plane using Eq. (7), it becomes a semicircle as Fig. 3. This equation can be expressed alike a Cole-Cole semicircular that K. S. Cole and R. H. Cole had asserted in the most of organic materials[9,10].

Using Eq. (2), we can express frequency-dependent R_p and C_p in terms of Z' and Z'' as follows.

$$R_p=(Z'-R_s)+\frac{(Z'')^2}{(Z'-R_s)} \tag{8}$$

$$C_p=-[\frac{1}{\omega R_p}][\frac{(Z'')}{(Z'-R_s)}] \tag{9}$$

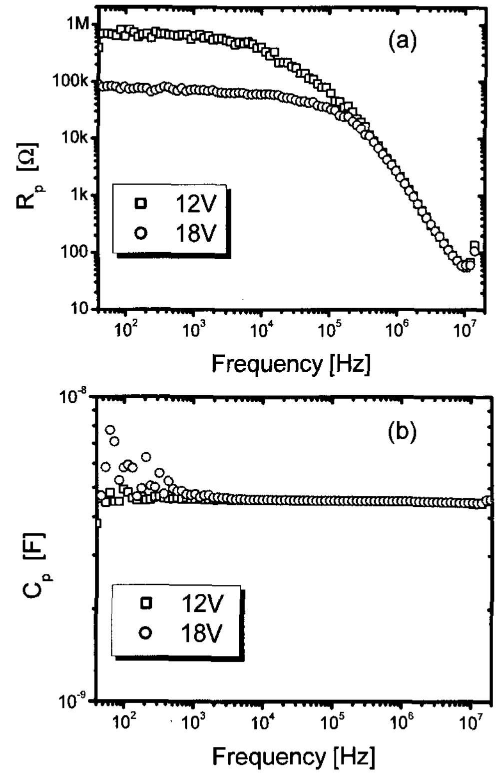


Fig. 4. Frequency-dependent R_p and C_p at the bias voltage 12 V and 18 V in ITO/Alq3/Al organic light-emitting diode.

Figure 4 shows a calculated resistance R_p and capacitance C_p of the device as a function of frequency at two bias voltages by applying the equivalent-circuit model of Fig. 2. If we see the resistance R_p in Fig. 4(a) measured at 18 V, the resistance decreases from ~80 kΩ to ~70 kΩ as the frequency increases from 40 Hz to 100 Hz. In the frequency range from 100 Hz to 10^4 Hz, the resistance is almost constant which is about 73 kΩ . Above 2×10^4 Hz, the resistance monotonically decreases. The behavior of frequency-dependent resistance R_p measured at 18 V is, in general, similar to the one measured at 12 V. In Fig. 4(b), a capacitance C_p is almost constant to be about 4.5 nF in the measured frequency range irrespective of the bias voltage.

4. CONCLUSION

An equivalent-circuit analysis was studied in the device structure of ITO/Alq3/Al with a thickness of Alq3 of 100 nm. We were able to analyze the equivalent circuit in organic light-emitting diode in terms of resistance and capacitance of complex impedance with thickness and frequency variation. Equivalent-circuit model of organic light-emitting diode can be established using a parallel combination of resistance R_p and capacitance C_p with a small series resistance R_s.

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