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Effect of Electric-Field on the Dependence of the Delay Time of Organic Light Emitting Diodes

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Abstract

The delay time of organic light emitting diodes (OLEDs) has three components: (i) The charge injection time, t_{inj}, which is the time taken to charge the metal/organic interface to the threshold voltage (V_{th}) by the injection of the charge carriers from the electrodes by Richardson-Schottky model (at low voltage) or Fowler-Northeim tunelling model (at high voltage), (ii) the charge running delay, t_{run}, is the time when the charge carriers run through the organic layer, and (iii) the recombination delay is the time when holes penetrating organic / organic interface recombine with electrons. The values of threshold voltage, time constant of OLEDs, zero-field charge carrier mobility and the electric field coefficient to the mobility can be determined from the measurement of the dependence of delay time on the strength of applied electric field.

Keywords: Delay time, OLEDs, Recombination, Charge injection

1. INTRODUCTION

Organic light emitting diodes OLEDs have been intensively investigated in the past 20 years[1], because of their applications in flat panel displays, Electroluminescence(EL) emission from OLEDs mainly consists of three processes : charge injection from the electrodes into the organic layer, charge transport in the bulk and electon- hole recombination. The EL response is closely related to all of these processes.

Several studies on the delay time of electroluminescence from OLEDs have been reported. Wang et al.[2] used an equivalent circuit model consisting of a fixed capacitance connected in parallel with a nonlinear resistance to estimate the delay time. Unfortunately further research[3] revealed that the equivalent circuit model is relatively ineffective in the case of higher electric field. Based on the assumption that the EL delay time can be divided into charge injection time and transport time.Wei et al.[3] and Ichikawa et al.[4] have derived the formulae of EL delay time. Their simulated results are consistent well with the experimental data for devices with a LiF/Al cathode. However, for other cathode species the simulation values are less than the measurement.

The present paper reports the effect of electric-field on the dependence of the delay time of organic light emitting diodes.

2. THEORY AND EXPERIMENTAL SUPPORT

Basically, the EL delay time should depend on two components : (i) the charge injection delay time, t_{inj}, and (ii) the charge running delay, t_{run}. Thus, the EL delay time may be expressed as

$$t_d = t_{inj} + t_{run} \qquad (1)$$

Considering the equivalent circuit of the OLED device to be a series connected circuit of a resistor and a capacitor (consisting of the anode and cathode of the OLED), the voltage difference at a time (t) can be expressed as an exponential growth function in the following way

$$E = E_0\left[1-\exp\left(\frac{-t}{\tau}\right)\right] \qquad (2)$$

where E_0 is the electric field strength of the applied pulse voltage, and τ is the time constant of the OLED device with the drive system. Using eq. (2), the injection delay can be expressed as

$$t_{inj} = -\tau\ln\left(1-\frac{E_{th}}{E_0}\right) = \tau_i S\frac{E_{th}}{E_0} = (R+R_0)C_i S\frac{E_{th}}{E_0}\,(for E_{th} << E_0) \qquad (3)$$

where, E_{th} is the threshold electric strength for charge injection. τ_i is the specific time constant per unit area of the time constant τ, and S is the cross–sectional area of OLED, and R, Ro and C_i represent the series resistance of OLEDs mainly caused by ITO (Indium - Tin-Oxide), the additional series resistance of the drive system and the specific capacitance per unit area of the OLED, respectively. As such, the transit time, in which the carriers will travel a distance, d, which is thickness of electron or hole transporting layer, can be obtained from the following equation

$$d = \int_{t_{inj}}^{t_{inj}+t_{run}} \mu E dt \tag{4}$$

where E is the strength of electric field at any time t, and μ is the mobility of the charge carriers.
In organic semiconductors, the charge mobility is electric–field dependent and it can be expressed as

$$\mu = \mu_0 \exp\left(\gamma\sqrt{E}\right) \tag{5}$$

where, μ_o is the zero–field mobility and γ is the electric–field coefficient to the mobility.
Using eqs. (2), (4), and (5),and neglecting higher orders of t and τ, we get

$$d = \mu_0 E_0 \left[t_{inj} + t_{run} + \tau \exp\left\{ -\frac{\left(t_{inj} + t_{run}\right)}{\tau} \right\} \right.$$
$$\left. \exp\left\{ \gamma\sqrt{E_0}\sqrt{1 - \exp\frac{\left(t_{inj} + t_{run}\right)}{\tau}} \right\} \right.$$
$$- \mu_0 E_0 \left[t_{inj} + \tau \exp\left(-\frac{t_{inj}}{\tau} \right) \exp\left\{ \gamma \sqrt{E_0 \sqrt{1-} \exp < \frac{-t_{inj}}{\tau} > \ )} \right\} \right] \tag{6}$$

Now, we consider the following three cases:

Case I : $\tau << (t_{inj}+t_{run})$ or $\tau << t_{inj}$

In low field regime and for low value of the time constant τ of OLED, $\tau << (t_{inj} + t_{run})$ or t_d and, $\tau < t_{inj}$, and, therefore, for low value of τ, we get

$$t_d = \frac{d}{\mu E_0} = \frac{d^2}{\mu V_0} = \frac{d^2}{\mu_0 V_0} \exp\left(-\beta V_0\right) \tag{7}$$

where, $V_o = E_o$ d, is the applied voltage and β is the characteristic constant for the dependence of log of mobility on $E^{1/2}$.

Case II : $\tau >> (t_{inj} + t_{run})$ or t_d and $\tau >> t_{inj}$

In high field regime, t_{inj} and t_{run} may become low as compared to τ, and thus for $\tau > (t_{inj} + t_{run})$ and $\tau > t_{inj}$ and therefore for $\tau >> (t_{inj} + t_{run})$, we get

$$t_d = \tau_i S \frac{E_{th}}{E_0} \tag{8}$$

Case III : τ comparable with t_{inj} and t_{run}

In this case, from eq. (6), t_d may be expressed as

$$t_d = \frac{d}{\mu_0 E_0} + \tau_i S \left[\exp\left(\frac{t_{inj}}{\tau}\right) \exp\left\{ \gamma \sqrt{E_0 \left(1 - e^{\frac{-t_i}{\tau}}\right)} \right\} \right]$$
$$+ \tau_i S \left[-\exp\left\{\frac{-t_d}{\tau}\right\} \exp\left\{ \gamma \sqrt{E_0 \left(1 - e^{\frac{-t_d}{\tau}}\right)} \right\} - \left\{ \ln\left(1 - \frac{E_{th}}{E_0}\right) \right\} \right] \tag{9}$$

Thus, for $E_{th} < E_o$ and $\tau < t_d$, eq. (9) may be expressed as

$$t_d = mS + t_{d0} \tag{10}$$

where

$$m = \tau_i \left[e^{\gamma\sqrt{E_{th}}} - e^{\frac{t_d}{\tau_e}} e^{\gamma\sqrt{E_0}} \right] \tag{11}$$

is the slope between t_d versus S plot, and

$$t_{d0} = \frac{d}{\mu_0 E_0} \tag{12}$$

is the intercept on t_d axis.

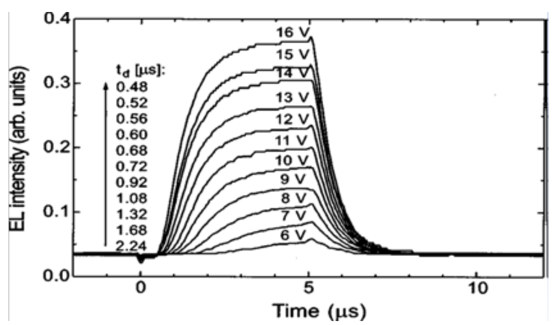

Fig.1. Voltage dependence of the transient EL from an ITO/CuPc-20nm/NPB-45nm/Alq_3-50nm/Mg:Ag, multilayer OLED. The pulse width was 5μs and the repetition rate 1khz [after Barth et al., ref. [5].

Fig. 1. shows the EL response produced during the application of a voltage pulse of duration 5 μs on ITO/CuPc/NPB/Alq_3/Mg:Ag , multi layer device. It is seen that initially after a certain time delay t_d the EL intensity increases with time, attains a saturation value

and then it decays with time, in which the decay starts just after the turning off of the applied voltage pulse. It is evident that the delay time t_d decreases with increasing value of the applied voltage.

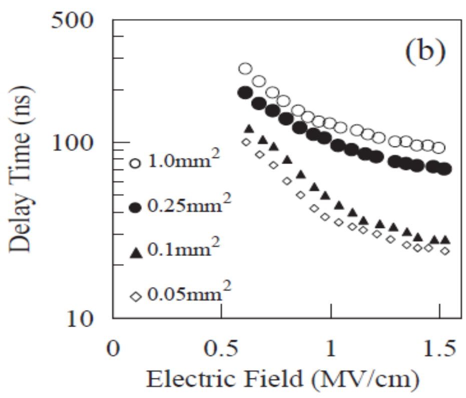

Fig.2. Electric field dependence of the delay time in ITO/α-NPD(50nm)/Alq_3(30nm)/Mg:Ag for different active areas [after (Kajii et al., ref.[6].

Fig.2.illustrates the semi log plot between the delay time t_d and the electric field. It is seen that initially the delay time decreases with the electric field at a fast rate, and then it decreases at a slow rate.

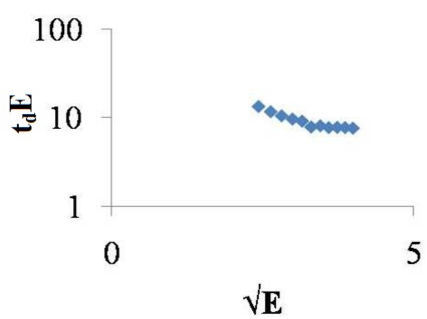

Fig.3. The semilog plot of t_d E versus√ E for an ITO/CuPc-20nm/NPB-45nm/Alq_3-50nm/Mg:Ag multi layer OLED

Fig.3. shows the semilog plot of t_d E versus√ E for this multi layer OLED. It is seen that initially the plot decreases linearly with √E in which the slope is negative. Later on the slope decreases very slowly with increasing value of √E , such result is expected from equation.

3. CONCLUSION

The time delay between the time of application of the electric pulse and the onset of electroluminescence in the device is called delay time. The delay time decreases with increasing value of the applied voltage, initially at a fast rate and then at a slow rate. It is found that the delay time should also decrease with increasing value of the mobility of charge carrier with increasing electric field. The injection delay time should increase with increasing surface area of the OLED devices. It seems that the initial fast decrease of OLED delay time with increasing electric field occurs for the transit delay time. For high electric field the transit delay time becomes negligible as compared to the injection delay time, and therefore, at high electric field the delay time decreases slowly with increasing electric field. From the field dependence of the delay time the mobility of charge carrier and the characteristic constant β for the dependence of log of mobility on $E^{1/2}$ can be determined

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