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Numerical Investigation of Fast Dynamic Response of Organic Light-Emitting Diodes

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Abstract – **We make a numerical investigation of transient responses of organic light-emitting diodes (OLEDs) to various device and material parameters such as the device length, carrier mobility, energy level offset, exciton lifetime, barrier height, and recombination rate. We have found that the delay time is mainly determined by the device length and bias voltage, whereas the rise time depends on the electron mobility and recombination rate. This study may provide design guidelines of OLEDs for applications in high-speed visible light communications (VLC).**

I. INTRODUCTION

Extensive researches on organic light-emitting diodes (OLEDs) as a light source for applications including flat panel displays and lightings have been made [1]. Recently, solid-state lightings (i.e., LEDs and OLEDs) have attracted a great deal of attention as a lighting source for visible light communications (VLC) [2], [3]. For applications in high-speed VLC, OLEDs featuring fast dynamic behaviours are demanded since most of the molecular materials behave electrically like an insulator, the carrier mobility by which is very low ($10^{-3} \sim 10^{-7}$ cm^2/Vs). It is known that the response speed of OLEDs is determined by the electronic process; i.e., carrier injection, carrier transport, space charge accumulation, local exciton generation, and finally exciton radiative decay. To investigate such dynamic behaviours, numerical modeling and simulation are essential, enabling us to predict and perceive the complex behaviours of OLEDs. Mathematical models [4]-[6] considering the current injection into organic materials, the hopping transport of carriers, the locally generated excited states, and the radiative decay of excitons have been widely used for the accurate description of the underlying physics for the operation of OLEDs. The model [5], [6] that consists of Poisson's equation and time-dependent drift-diffusion equations can describe the complex interaction among the important material parameters such as field-dependent carrier mobility, Schottky barrier height, energy offset at the organic/organic interfaces, etc. With the numerical model, in this paper, we carry out a numerical study of transient responses of OLEDs to various device and material parameters such as the device length, carrier mobility, energy level offset, exciton lifetime, barrier height, and recombination rate. The model can visualize clear device characteristics such as the spatial charge density distribution, electric field distribution, exciton density distribution, and current balance.

II. MODEL

A. *Poisson's Equation;*

$$E(z+\Delta z/2,t)=E(z-\Delta z/2,t)+\Delta z\frac{q}{\varepsilon}\{p(z,t)-n(z,t)+N_D(z)-N_A(z)\} \quad (1)$$

where the variable $E(z,t)$ (V/cm) denotes the electric field, Δz (cm) the cell width discretized in space, $n(z,t)$ (cm^{-3}) and $p(z,t)$ (cm^{-3}) the electron and hole densities, respectively, and $N_D(z)$ (cm^{-3}) and $N_A(z)$ (cm^{-3}) the donor and acceptor impurity concentrations, respectively.

B. *Drift-Diffusion Equation;*

$$n(z,t+\Delta t)=n(z,t)+\Delta t\left\{\frac{1}{q}\frac{J_n(z+\Delta z/2,t)-J_n(z-\Delta z/2,t)}{\Delta z}-r(z,t)n(z,t)p(z,t)\right\}$$

$$p(z,t+\Delta t)=p(z,t)-\Delta t\left\{\frac{1}{q}\frac{J_p(z+\Delta z/2,t)-J_p(z-\Delta z/2,t)}{\Delta z}+r(z,t)n(z,t)p(z,t)\right\} \quad (2)$$

where

$$\begin{aligned}J_n(z+\Delta z/2,t)&=q\mu_n(z+\Delta z/2,t)\frac{n(z,t)+n(z+\Delta z,t)}{2}E(z+\Delta z/2,t)+\\&\quad kT\mu_n(z+\Delta z/2,t)\frac{n(z+\Delta z,t)-n(z,t)}{\Delta z}\\J_p(z+\Delta z/2,t)&=q\mu_p(z+\Delta z/2,t)\frac{p(z,t)+p(z+\Delta z,t)}{2}E(z+\Delta z/2,t)-\\&\quad kT\mu_p(z+\Delta z/2,t)\frac{p(z+\Delta z,t)-p(z,t)}{\Delta z}\end{aligned} \quad (3)$$

with the variable μ_n (cm^2/Vs) defined as the electron mobility, μ_p (cm^2/Vs) the hole mobility, k (J/K) the Boltzmann constant, and T (=300K) the temperature.

C. *Exciton Rate Equation;*

After solving (1) and (2), the exciton density distribution can be obtained by updating the following rate equation:

$$S(z,t+\Delta t)=S(z,t)+\Delta t\left\{\begin{aligned}&\frac{1}{4}r(z,t)n(z,t)p(z,t)-\frac{S(z,t)}{\tau_s}-Q(z)\frac{S(z,t)}{\tau_q}+\\&D_s\frac{S(z+\Delta z,t)-2S(z,t)+S(z-\Delta z,t)}{\Delta z^2}\end{aligned}\right\} \quad (4)$$

where S (cm^{-3}) indicates the singlet exciton density. More detailed description of the model including boundary conditions for the electric field and current injection into the organic materials is provided in [5].

III. RESULTS AND DISCUSSION

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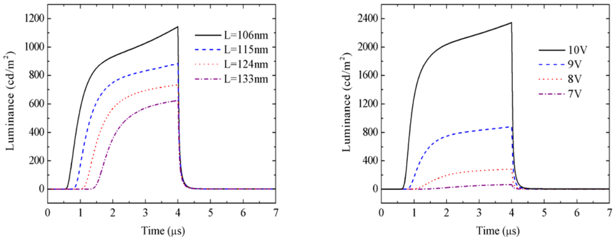
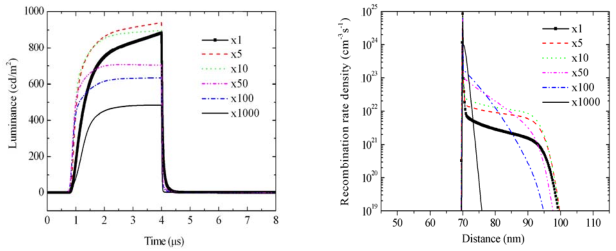
The OLED structure under investigation is composed of a 150-nm-thick indium-tin-oxide (ITO) pre-coated on a glass substrate, 20-nm-thick copper phthalocyanine (CuPc), 50-nm-thick N,N′-diphenyl-N,N′-bis(1-naphthyl)-1-1′biphenyl-4,4″diamine (α-NPD) for a hole transport layer (HTL), 45-nm-thick Tris (8-hydroxyquinoline) aluminum (Alq_3) for an electron transport layer (ETL), 1-nm-thick lithium fluoride (LiF), and 100-nm-thick aluminum (Al). For simulations, the pulsed bias voltage is applied. The pulse length is 4 μs and the repetition rate is 125 kHz.



(a) (b)

Fig. 1. Simulation results of transient EL (a) for different device lengths and (b) for different bias voltages.

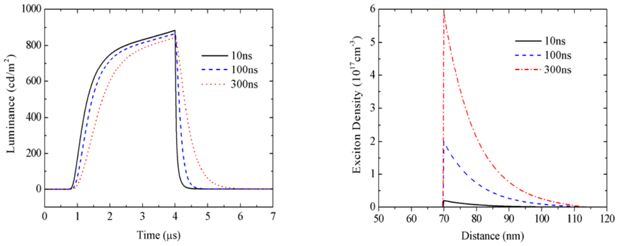
Shown in Fig. 1(a) is the simulation result of transient electroluminescence (EL) for different device lengths. The delay time, defined as the time until the injected holes and electrons meet inside the device, is one of key factors determining the speed of data transmission. The easiest way to decrease the delay time for high-speed communications is to reduce the overall device length, as demonstrated in Fig. 1(a). To ensure the device reliability, however, there must be a limit for a reduction of the device length. Meanwhile, the delay time varies depending sensitively on the bias voltage. As evident in Fig. 1(b), the delay time decreases with increasing bias voltage in the "on-state". It is attributed to the fact that the carrier mobility is increased in proportion to the electric field.



(a) (b)

Fig. 2. Simulation results of (a) transient EL for different electron mobilities and (b) recombination rate density distribution over the device length for different electron mobilities.

It is likely that higher carrier mobility would bring in shorter delay time as the EL delay upon turn-on is mainly determined by the electron transport. To verify it, we have increased the electron mobility of Alq_3 from 1.2×10^{-6} cm^2/Vs up to 1.2×10^{-3} cm^2/Vs. Contrary to expectations, a noticeable reduction in the delay time was not observed, as seen in Fig. 2(a). Instead, it speeds up the rise of EL upon turn-on. When the electron mobility is increased by an order of magnitude, the luminance is shown to be increased. Increasing the electron mobility further, however, causes a reduction of luminance. It is due most likely to the fact that the recombination zone is shrunk with increasing electron mobility (Fig. 2(b)). In bilayer OLEDs, holes reach first the HTL/ETL interface and penetrate into the ETL as the hole mobility is about two orders of magnitude higher than the electron mobility. This builds up the recombination zone inside the ETL layer near the HTL/ETL interface. As the electron mobility increases, however, more electrons reach the HTL/ETL interface without recombination, thereby reducing the recombination zone and the luminance.



(a) (b)

Fig. 3. Simulation results of (a) transient EL for different exciton lifetimes and (b) exciton density distribution over the device length for different exciton lifetimes.

We have further investigated the effect of the exciton lifetime on EL dynamics. Shown in Fig. 3(a) is the dynamic response of EL to different exciton lifetimes. With increasing exciton lifetime, both the rise time and the decay time are getting increased since photon generation decreases upon turn-on and lasts long upon turn-off, which is undesirable for high-speed communications. As the exciton lifetime increases, a larger number of excitons exist inside the device without making a contribution to photon generation (Fig. 3(b)).

Further simulation results and discussion regarding transient EL in response to the energy level offset, barrier height, and recombination rate will be presented in the conference.

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