Vol 12 No 7, July 2003
1009-1963/2003/12(07)/0796-07

Chinese Physics

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Numerical investigations on the current conduction in bilayer organic light-emitting devices with ohmic injection of charge carriers*

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(Received 8 January 2003; revised manuscript received 18 February 2003)

A numerical model for bilayer organic light-emitting diodes (OLEDs) has been developed on the basis of trapped charge limited conduction. The dependences of the current density on the operation voltage, the thickness and trap properties of the hole transport layer (HTL) and emission layer (EML) in bilayer OLEDs of the structure anode/HTL/EML/cathode have been numerically investigated. It has been found that, for given values of reduced trap depth, total trap density, and carrier mobility of HTL and EML, there exists an optimum thickness ratio of HTL to the sum of HTL and EML, by which a maximal current density, and hence maximal quantum efficiency and luminance, can be achieved. The current density decreases quickly with the mean trap density, and decreases nearly exponentially with the mean reduced trap depth.

Keywords: numerical simulation, organic light-emitting diodes, current conduction
PACC: 7860F, 7280L, 7340S, 0260

1. Introduction

Organic light-emitting diodes (OLEDs) have received considerable attention since the first demonstrations of practical electroluminescent device based on molecular and polymer materials.[1−3] Their ease of fabrication, high efficiency, compatibility with flexible and curved substrates and prospect of low cost make them appealing candidates for display applications. For the simplest device structure, an organic electroluminescent layer sandwiched between two metal electrodes (single layer OLED), a number of theoretical studies regarding the injection and transport of charge carriers have been carried out.[4−8] Although ease to fabricate, single layer OLEDs are generally inefficient. Two principal factors limit the efficiency of single layer OLEDs, (1) different electron and hole mobilities cause the recombination to occur near an electrode, where dipole quenching and nonradiative losses reduce device efficiency; and (2) unbalanced carrier injection results in a large fraction of one carrier type traversing the device without recombination. Bilayer OLEDs, generally composed of two organic layers sandwiched between two electrodes, are able to overcome these difficulties by controlling the distribution of carriers in the device using discontinuities in either the energy levels or carrier mobilities or the thickness of the two organic materials used to fabricate the device. In bilayer OLEDs, one organic layer is responsible for light emission, called emission layer (EML), and the other is responsible for hole transport and electron blockade, the hole transport layer (HTL) (for n-type luminescent materials) (Fig.1), or for electron transport and hole blockade, the electron transport layer (ETL) (for p-type luminescent materials). Under application of a proper bias, holes will be injected from the anode into the HTL and electrons will be injected from cathode into the EML. The injected holes and electrons migrate towards the HTL/EML interface, and light will be emitted through the recombination of holes and electrons in the EML near the interface. Recent work of Nikitenko and Bässler was devoted to analytical modelling of bilayer OLEDs on the basis of an empirical formula of field dependent carrier mobility.[9] In a previous paper,[8] we have pro-

*Project supported by the National Natural science Foundation of China (Grant No. 60076023) and The Natural Science Foundation of Gansu Province (Grant No. ZS021-A25-003-Z).

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posed a numerical model for single layer OLEDs on the basis of trapped charge limited (TCL) conduction theory.[10,11] We report in this work the extension of that model to bilayer OLEDs, and the numerical simulation results of the dependence of the current density on the operation voltage, the layer thickness and the trap properties of HTL and EML.

2. Numerical model

Organic luminescent materials have generally poor electric conductivity with carrier mobility ranges from 10^{-3} to $10^{-8}\mathrm{cm^2V^{-1}s^{-1}}$, and most of them are single carrier conducting. That is, they have either much higher conductivity for holes than for electrons, generally several orders of magnitude larger, or vice versa. So the contributions of electrons in the HTL and holes in the EML to the current are negligible in most cases. The following discussions are based on bilayer OLEDs with anode/HTL/EML/cathode structure (Fig.1), but the results are also valid for bilayer OLEDs with a structure of anode/EML/ETL/cathode. To simplify the problem, we assume: (1) In the HTL there exist only free and trapped holes as well as hole current and in the EML only free and trapped electrons as well as electron current, that is, electron density and electron current in HTL as well as hole density and hole current in EML are negligible; (2) the mobility of holes and electrons are independent of the electric field; (3) the energy barrier at HTL/EML interface is so small, that its influence to carrier conduction can be neglected. The electric potential ϕ, field F, total hole density p, total electron density n and current density j at position x in the HTL ($0 \le x \le d_\mathrm{p}$) or EML ($d_\mathrm{p} < x \le d$) are associated through following equations:

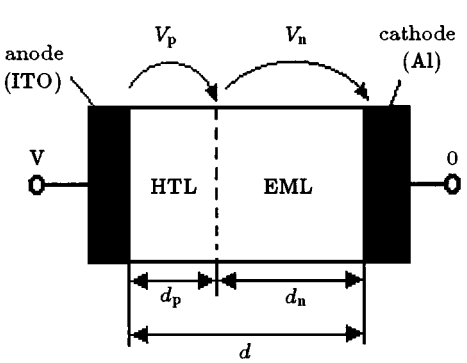


Fig.1. Structure of a bilayer OLED.

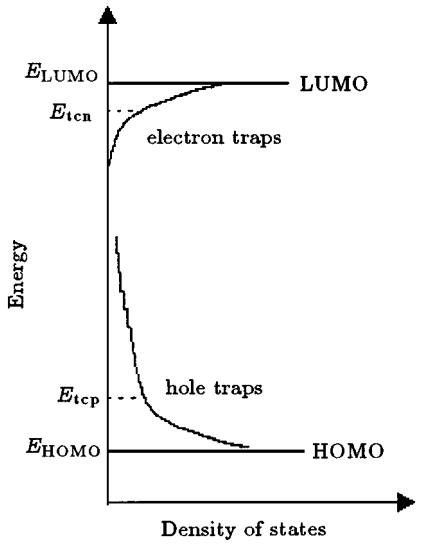


Fig.2. Exponential distribution of hole and electron traps.

$$\frac{\mathrm{d}F}{\mathrm{d}x} = \begin{cases} \dfrac{qp}{\varepsilon_0\varepsilon_\mathrm{rp}} & 0 \le x \le d_\mathrm{p}, \\ -\dfrac{qn}{\varepsilon_0\varepsilon_\mathrm{rn}} & d_\mathrm{p} < x \le d, \end{cases} \tag{1}$$

$$p = \begin{cases} p_\mathrm{f} + p_\mathrm{t} & 0 \le x \le d_\mathrm{p}, \\ 0 & d_\mathrm{p} < x \le d, \end{cases} \tag{2}$$

$$n = \begin{cases} 0 & 0 \le x \le d_\mathrm{p}, \\ n_\mathrm{f} + n_\mathrm{t} & d_\mathrm{p} < x \le d, \end{cases} \tag{3}$$

$$j = \begin{cases} q\mu_\mathrm{p}p_\mathrm{f}F - qD_\mathrm{p}\dfrac{\mathrm{d}p_\mathrm{f}}{\mathrm{d}x} & 0 \le x \le d_\mathrm{p}, \\ -q\mu_\mathrm{n}n_\mathrm{f}F + qD_\mathrm{n}\dfrac{\mathrm{d}n_\mathrm{f}}{\mathrm{d}x} & d_\mathrm{p} < x \le d, \end{cases} \tag{4}$$

$$F = -\frac{\mathrm{d}\phi}{\mathrm{d}x}. \tag{5}$$

Here q is the elementary charge, ε_0, ε_rp and ε_rn are the permittivity of vacuum, the relative dielectric constant of the HTL and EML, respectively; p_f and p_t are concentrations of free holes and trapped holes in the HTL, respectively, and n_f and n_t are that of electrons in EML. μ_p and D_p are the mobility and diffusion coefficient of holes in the HTL, and μ_n and D_n are that of electrons in EML; d_p, d_n and d are the thickness of the HTL, EML and the sum of them, respectively. k_B is the Boltzmann constant and T the ambient temperature. The zero point of coordinate x is located at the anode/HTL interface.

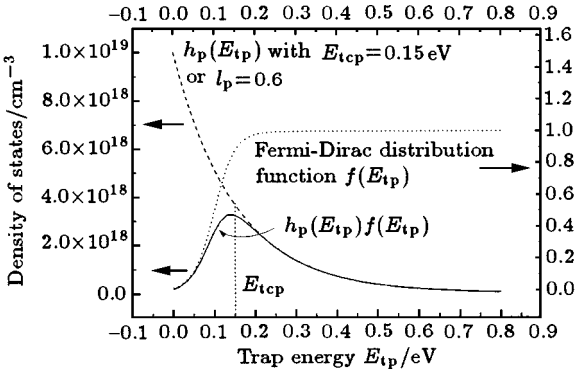


Fig.3. Density distribution of hole traps (dashed line) and the energy distribution of trapped holes (solid line). The zero point of $E_{\rm tp}$ is at $E_{\rm HOMO}$.

Assuming that Einstein relation is still valid, we have:

$$D_{\rm p} = \frac{\mu_{\rm p} k_{\rm B} T}{q}, \tag{6}$$

$$D_{\rm n} = \frac{\mu_{\rm n} k_{\rm B} T}{q}. \tag{7}$$

Experimental results show that the transport of charge carriers in organic materials can be described by trapped charge limited conduction with an exponential trap distribution (TCL). According to TCL theory, the trap density in organic layer are distributed in energy as follows:[12]

$$h_{\rm p}(E_{\rm tp}) = \frac{H_{\rm tp}}{k_{\rm B} T l_{\rm p}} {\rm e}^{-\frac{E_{\rm tp}}{k_{\rm B} T l_{\rm p}}}, \tag{8}$$

$$h_{\rm n}(E_{\rm tn}) = \frac{H_{\rm tn}}{k_{\rm B} T l_{\rm n}} {\rm e}^{-\frac{E_{\rm tn}}{k_{\rm B} T l_{\rm n}}}, \tag{9}$$

where $E_{\rm tp}$ is the energy of hole trap-states respective to the energy of the highest occupied molecular orbit (HOMO) (Fig.2), and $E_{\rm tn}$ is the energy of electron trap states respective to the lowest unoccupied molecular orbital (LUMO); $h_{\rm p}$ ($E_{\rm tp}$) is the density of hole trap states per unit energy in the vicinity of trap energy $E_{\rm tp}$, and $h_{\rm n}$ ($E_{\rm tn}$) is that of electron traps. $l_{\rm p}$ and $l_{\rm n}$ are the reduced trap depths, which are defined as the ratio of the characteristic trap energy of trap distribution to thermal energy $k_{\rm B}T$, that is $l_{\rm p} = E_{\rm tcp}/k_{\rm B}T$ and $l_{\rm n} = E_{\rm tcn}/k_{\rm B}T$. $H_{\rm tp}$ and $H_{\rm tn}$ are the total density of hole trap states and electron trap states, respectively. The density of trapped holes or trapped electrons can be obtained by the integration of the product of $h_{\rm p}$ ($E_{\rm tp}$) or $h_{\rm n}$ ($E_{\rm tn}$) and proper Fermi–Dirac distribution function over the trap energies in the range $[0, +\infty]$ or $[-\infty, 0]$ (Fig.3). In organic semiconductors, the concentration of free charges $\rho_{\rm f}$ is generally much smaller than that of the total charges ρ, and they are associated through following Eqs [13]

$$\rho_{\rm f} = \begin{cases} \theta \rho^{l_{\rm p}} & 0 \le x \le d_{\rm p}, \\ \theta \rho^{l_{\rm n}} & d_{\rm p} < x \le d, \end{cases} \tag{10}$$

$$\rho = \begin{cases} qp & 0 \le x \le d_{\rm p}, \\ -qn & d_{\rm p} < x \le d, \end{cases} \tag{11}$$

$$\rho_{\rm f} = \begin{cases} qp_{\rm f} & 0 \le x \le d_{\rm p}, \\ -qn_{\rm f} & d_{\rm p} < x \le d, \end{cases} \tag{12}$$

$$\theta = \begin{cases} qN_{\rm HOMO} \left(\dfrac{\sin\left(\dfrac{\pi}{l_{\rm p}}\right)}{qH_{\rm tp}\left(\dfrac{\pi}{l_{\rm p}}\right)} \right)^{l_{\rm p}} & 0 \le x \le d_{\rm p}, \\ -qN_{\rm LUMO} \left(\dfrac{\sin\left(\dfrac{\pi}{l_{\rm n}}\right)}{qH_{\rm tn}\left(\dfrac{\pi}{l_{\rm n}}\right)} \right)^{l_{\rm n}} & d_{\rm p} < x \le d, \end{cases} \tag{13}$$

where $N_{\rm HOMO}$ and $N_{\rm LUMO}$ are the density of states of the HOMO and LUMO, respectively. Substituting Eqs.(11)–(13) into Eq.(10), we obtain

$$p_{\rm f} = N_{\rm HOMO} \left(\frac{\sin\left(\dfrac{\pi}{l_{\rm p}}\right)}{H_{\rm tp}\left(\dfrac{\pi}{l_{\rm p}}\right)} \right)^{l_{\rm p}} p^{l_{\rm p}}, \tag{14}$$

$$n_{\rm f} = N_{\rm LUMO} \left(\frac{\sin\left(\dfrac{\pi}{l_{\rm n}}\right)}{H_{\rm tn}\left(\dfrac{\pi}{l_{\rm n}}\right)} \right)^{l_{\rm n}} n^{l_{\rm n}}. \tag{15}$$

For the convenience of derivation of formula, dimensionless quantities γ, E, u, s, and i, which are called respectively the reduced charge density, reduced electric field, reduced voltage, reduced position and reduced current density, are defined as follows:

$$\gamma = \begin{cases} \dfrac{qd_{\rm p}^2}{\varepsilon_0 \varepsilon_{\rm rp} k_{\rm B} T l_{\rm p}} \rho & 0 \le x \le d_{\rm p}, \\ \dfrac{qd_{\rm n}^2}{\varepsilon_0 \varepsilon_{\rm rn} k_{\rm B} T l_{\rm n}} \rho & d_{\rm p} < x \le d, \end{cases} \tag{16}$$

$$E = \begin{cases} \dfrac{qd_{\rm p}}{k_{\rm B} T l_{\rm p}} F & 0 \le x \le d_{\rm p}, \\ \dfrac{qd_{\rm n}}{k_{\rm B} T l_{\rm n}} F & d_{\rm p} < x \le d, \end{cases} \tag{17}$$

$$u = \begin{cases} \dfrac{q}{k_{\rm B} T l_{\rm p}} V_{\rm p} & 0 \le x \le d_{\rm p}, \\ \dfrac{q}{k_{\rm B} T l_{\rm n}} V_{\rm n} & d_{\rm p} < x \le d, \end{cases} \tag{18}$$

$$i = \begin{cases} \left(\dfrac{q}{k_{\rm B} T l_{\rm p}} \right)^{l_{\rm p}} \dfrac{d_{\rm p}^{2l_{\rm p}+1}}{\mu_{\rm p} \theta (\varepsilon_0 \varepsilon_{\rm rp})^{l_{\rm p}}} j & 0 \le x \le d_{\rm p}, \\ \left(\dfrac{q}{k_{\rm B} T l_{\rm n}} \right)^{l_{\rm n}} \dfrac{d_{\rm n}^{2l_{\rm n}+1}}{\mu_{\rm n} \theta (\varepsilon_0 \varepsilon_{\rm rn})^{l_{\rm n}}} j & d_{\rm p} < x \le d, \end{cases} \tag{19}$$

$$s = \frac{x}{d}. \tag{20}$$

The value of the reduced position s is between 0 and 1.

Substituting Eqs.(6), (7), (10), (17) and (19) into Eq.(4), we have

$$i = \begin{cases} E\gamma^{l_\mathrm{p}} - \gamma^{l_\mathrm{p}}\gamma^{l_\mathrm{p}-1}\dfrac{\mathrm{d}\gamma}{\mathrm{d}s} & 0 \le x \le d_\mathrm{p}, \\ -E\gamma^{l_\mathrm{n}} - \gamma^{l_\mathrm{n}}\gamma^{l_\mathrm{n}-1}\dfrac{\mathrm{d}\gamma}{\mathrm{d}s} & d_\mathrm{p} < x \le d, \end{cases} \tag{21}$$

$$\frac{\mathrm{d}E}{\mathrm{d}s} = \begin{cases} \gamma & 0 \le x \le d_\mathrm{p}, \\ -\gamma & d_\mathrm{p} < x \le d. \end{cases} \tag{22}$$

For the convenience of predigesting the above equations, dimensionless variables z and y are defined as:

$$z = \begin{cases} i^{-\frac{1}{2l_\mathrm{p}+1}}E & 0 \le x \le d_\mathrm{p}, \\ i^{-\frac{1}{2l_\mathrm{n}+1}}E & d_\mathrm{p} < x \le d, \end{cases} \tag{23}$$

$$y = \begin{cases} i^{-\frac{2}{2l_\mathrm{p}+1}}\gamma & 0 \le x \le d_\mathrm{p}, \\ i^{-\frac{2}{2l_\mathrm{n}+1}}\gamma & d_\mathrm{p} < x \le d. \end{cases} \tag{24}$$

Substituting them into Eqs.(21) and (22), we have

$$\frac{\mathrm{d}y}{\mathrm{d}z} = z - \frac{1}{y^{l_\mathrm{p}}} \quad 0 \le x \le d_\mathrm{p}, \tag{25}$$

$$\frac{\mathrm{d}y}{\mathrm{d}z} = z + \frac{1}{y^{l_\mathrm{n}}} \quad d_\mathrm{p} < x \le d. \tag{26}$$

It can be seen from Eqs.(25) and (26) that, y has minimum values $y_\mathrm{mp} = z_\mathrm{mp}^{-\frac{1}{l_\mathrm{p}}}$ at $z = z_\mathrm{mp}$, and $y_\mathrm{mn} = (-z_\mathrm{mn})^{-\frac{1}{l_\mathrm{p}}}$ at $z = z_\mathrm{mn}$. Eqs.(25) and (26) are solved by using standard numerical methods with the points $(z_\mathrm{mp}, y_\mathrm{mp})$ and $(z_\mathrm{mn}, y_\mathrm{mn})$ as starting values.

3. Results and discussion

Numerical solutions to Eqs.(25) and (26) for different values of z_mp and z_mn are shown in Fig.4. It is to seen that, the function $y(z)$ are unvaried for different values of z_mp when $z < 0$ and $0 \le x \le d_\mathrm{p}$, and for different values of z_mn when $z > 0$ and $d_\mathrm{p} < x \le d$. Fig.5 shows the dependences of current density to thickness ration d_p/d for different combinations of reduced trap depth $(l_\mathrm{p}, l_\mathrm{n})$ in the HTL and EML, under a constant d values (d=200nm). If the reduced trap depth $(l_\mathrm{p}, l_\mathrm{n})$, total trap density $(H_\mathrm{tp}, H_\mathrm{tn})$ and carrier mobility $(\mu_\mathrm{p}, \mu_\mathrm{n})$ in the HTL and EML are nearly equal, then the device will have maximum current, and hence maximal quantum efficiency and luminance, when d_p/d=0.5, or $d_\mathrm{p} = d_\mathrm{n}$ (Fig.1(a)). If the total trap density and carrier mobility in the HTL and EML are nearly equal, but the reduced trap depth is different, then the current density will be greater when the HTL is thicker than the EML for $l_\mathrm{p} < l_\mathrm{n}$, or when it is thinner than EML for $l_\mathrm{p} > l_\mathrm{n}$ (Fig.5(b)). Thus, in designing bilayer OLEDs using luminescent materials with deep trap states, high trap density and low electron mobility, hole transport material with shallow trap states, low trap density and high hole mobility should be chosen, and the EML should be made thinner than the HTL.

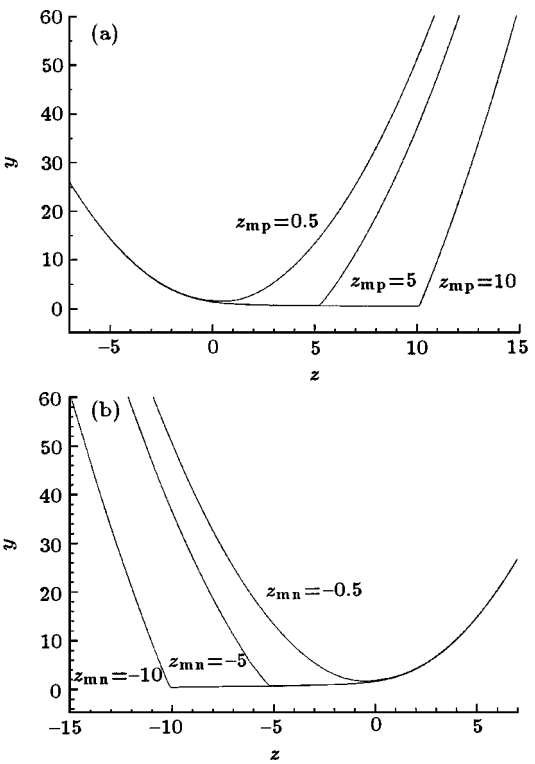


Fig.4. Numerical solutions to Eqs.(25) and (26) for different values of z_mp and z_mn with (a) for $0 \le x \le d_\mathrm{p}$ and (b) for $d_\mathrm{p} < x \le d$. The rest of parameters are $l_\mathrm{p} = l_\mathrm{n} = 2$.

On the contrary, when the reduced trap depth and the total trap density of EML are small and its electron mobility is high, then hole transport materials with deep trap states, high trap density and low hole mobility can be used, but the HTL must be made thinner than the EML. Naturally, the EML cannot be too thin, because, on one hand, pinhole problem can occur in ultra thin organic films, [14] and on the other, excitons generated by the recombination of holes and electrons can diffuse towards the boundary of the EML, and some of them will go out of the EML if the thickness of EML is less than the diffusion length of the excitons. In fact, the diffusion length of excitons in green luminescent organic material tris (8-quinolinolato) aluminium (Alq_3) has been determined to be about 20nm.[15]

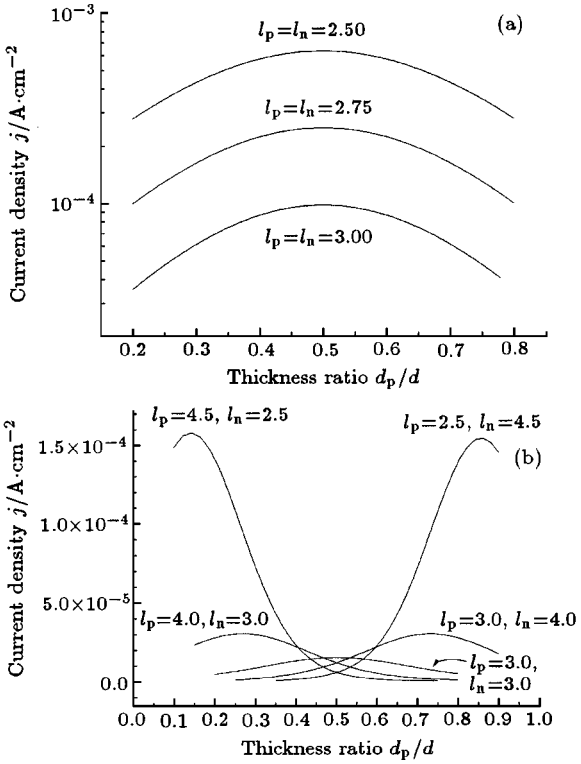


Fig.5. Calculated dependences of the current density on the thickness ratio d_p/d under a constant total thickness of the two organic layers, (a) and (b) for different values of l_p and l_n with $\mu_p = \mu_n = 1.0\times10^{-5}\mathrm{cm^2V^{-1}s^{-1}}$, $H_{tp}=H_{tn} = 1.0\times10^{19}\mathrm{cm^{-3}}$. The rest of parameters used for this simulation are: d=200nm, $N_{HOMO} = N_{LUMO} = 1.0\times10^{20}\mathrm{cm^{-3}}$, $\varepsilon_{rp}=\varepsilon_{rn}=2.0$, T=300K, V=10V.

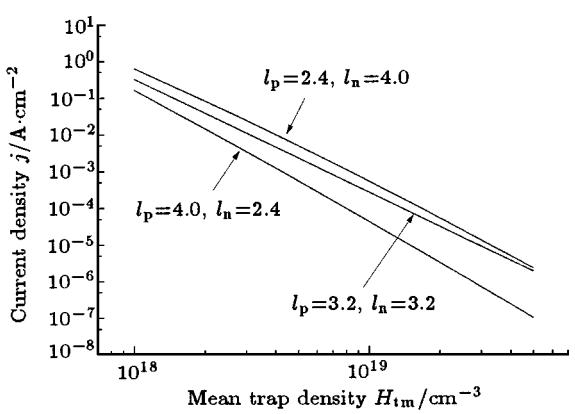


Fig.6. Calculated dependences of the current density on the mean trap density with d=200nm, d_p/d=2/3, H_{tp}/H_{tn}=1, $\mu_p = 10^{-4}\mathrm{cm^2V^{-1}s^{-1}}$ and $\mu_n = 10^{-5}\mathrm{cm^2V^{-1}s^{-1}}$, for different values of l_p and l_n.

In order to characterize the trap properties of the whole bilayer OLEDs, mean trap density H_{tm} and mean reduced trap depth l_m are defined as follows:

$$H_{tm} = \frac{d_p H_{tp} + d_n H_{tn}}{d_p + d_n}, \tag{27}$$

$$l_m = \frac{d_p H_{tp} l_p + d_n H_{tn} l_n}{d_p H_{tp} + d_n H_{tn}}. \tag{28}$$

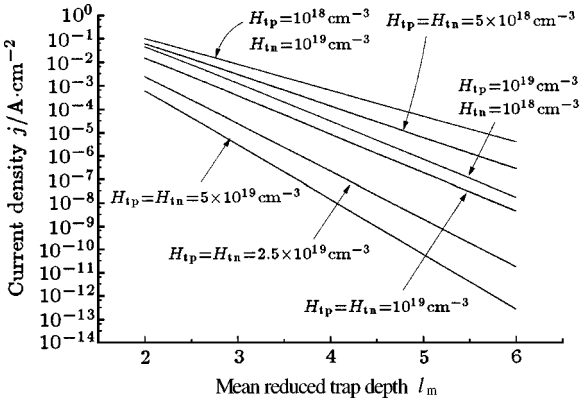


Fig.7. Calculated dependences of the current density on the mean reduced trap depth with d=200nm, d_p/d=2/3, $l_p=l_n$, $\mu_p=10^{-4}\mathrm{cm^2V^{-1}s^{-1}}$, $\mu_n=10^{-5}\mathrm{cm^2V^{-1}s^{-1}}$, for different values of H_{tp} and H_{tn}.

Figure 6 shows the dependences of the current density on the mean trap density H_{tm} for different values of l_p and l_n, with d=200nm, d_p/d=2/3, H_{tp}/H_{tn}=1, $\mu_p=10^{-4}\mathrm{cm^2V^{-1}s^{-1}}$ and $\mu_n=10^{-5}\mathrm{cm^2V^{-1}s^{-1}}$. It is seen that the current density decreases quickly as the mean trap density increases. An increase of one orders of magnitude of the mean trap density will result in a reduction of the current density for about 3 orders of magnitude. The dependences of the current density on the mean reduced trap depth for different values of H_{tp} and H_{tn} with d=200nm, d_p/d=2/3, $l_p=l_n$, $\mu_p=1.0\times10^{-4}\mathrm{cm^2V^{-1}s^{-1}}$, and $\mu_n=1.0\times10^{-5}\mathrm{cm^2V^{-1}s^{-1}}$ are shown in Fig.7. It is evident that, the logarithm of the current density decreases nearly linearly with the mean reduced trap depth, or the current density decreases exponentially with the mean reduced trap depth, and the greater the mean trap density H_{tm}, the steeper the decrease of the current density.

Figure 8 shows the calculated current-voltage characteristics for different values of hole and electron mobility as well as thickness ratio d_p/d, with l_p=2.5, l_n=4.5, $H_{tp}=H_{tn} = 10^{19}\mathrm{cm^{-3}}$, $N_{HOMO} = N_{LUMO} = 10^{20}\mathrm{cm^{-3}}$, $\varepsilon_{rp}=\varepsilon_{rn}=2$ and T=300K. It can be seen that, the higher the hole mobility, the greater the current density and its rate of increase for constant thickness ratio (d_p/d=0.85) and electron mobility ($\mu_n=10^{-5}\mathrm{cm^2V^{-1}s^{-1}}$) (curves 1, 2 and 3 in Fig.8). So when a n-type electroluminescent material with deep traps has been chosen for the EML, the hole conducting material for the HTL must have a hole mobility as high as possible, in order to achieve high

device current. If the carrier mobility of the HTL and EML are nearly equal, then the current will decrease with the thickness ratio d_p/d (curves 3, 5 and 6 in Fig.8), which is in consistent with the results shown in Fig.5(b). For constant thickness ratio (d_p/d=0.6) and hole mobility (μ_p=10^{-5}cm^{2}V^{-1}s^{-1}) in the HTL, current density increases with the electron mobility of the EML (curves 6 and 4 in Fig.8).

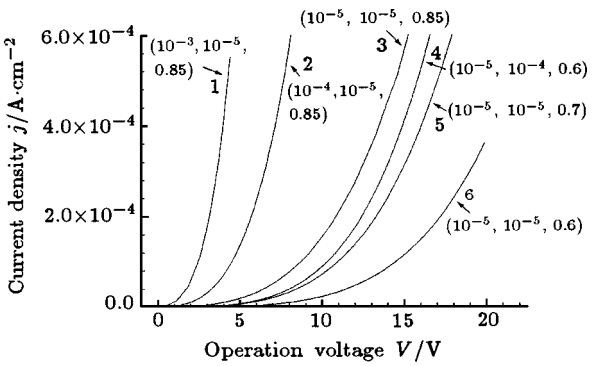


Fig.8. Calculated current-voltage characteristics for six different combinations of hole and electron mobility (in cm^{2}V^{-1}s^{-1}) as well as thickness ratio (μ_p, μ_n, d_p/d), with d=200nm, l_p=2.5, l_n=4.5, H_{tp}=H_{tn} = 10^{19}cm^{-3}, N_{HOMO} = N_{LUMO} = 10^{20}cm^{-3}, ε_{rp}=ε_{rn}=2.0 and T=300K.

An ITO/PEDOT: PSS/F8/CsF/Al device is a typical ohmic injection bilayer OLED, where PEDOT:PSS and F8 denote polystyrenesulfonic acid doped with poly (3, 4-ethylene dioxythiophene) and poly (9, 9-dioctylfluorene), and serve as the HTL and EML, respectively. The ultra thin CsF layer (4 nm) plays the role to reduce the energy barrier between Al and F8. Fig.9 shows the experimental and simulation result of current-voltage characteristics for this device. The experimental data from reference [16] are presented by filled circles and the solid line is the result of the simulation. The simulation parameters are d=130nm, d_p=60nm, l_p=4.4, l_n=5.6, $\mu_p = 2\times10^{-7}$cm^{2}V^{-1}s^{-1}, $\mu_n = 2\times10^{-8}$cm^{2}V^{-1}s^{-1}, $H_{tp} = 2\times10^{17}$cm^{-3}, $H_{tn} = 4\times10^{17}$cm^{-3}, N_{HOMO} = N_{LUMO} = 10^{20}cm^{-3}, ε_{rp}=ε_{rn}=2.0 and T=300K. The simulation result agrees very well with the experiment for operation voltage greater than 4.7V. The small discrepancy between simulation and experiment for operation voltage less than 4.7V is caused mainly by the energy barrier at HTL/EML interface, which is ignored in the simulation.

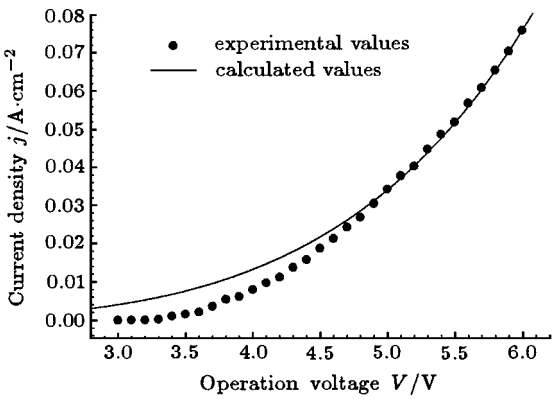


Fig.9. Experimental and simulation results of j-V dependences for ITO/G-PEDOT: PSS (60nm) /F8 (70nm) /CsF/Al bilayer OLED. The experimental data from reference [16] are presented by filled circles, while the solid line is the result of simulation. The parameters used in the simulation are d=130nm, d_p=60nm, l_p=4.4, l_n=5.6, $\mu_p = 2\times10^{-7}$cm^{2}V^{-1}s^{-1}, $\mu_n = 2\times10^{-8}$cm^{2}V^{-1}s^{-1}, $H_{tp} = 2\times10^{17}$cm^{-3}, $H_{tn} = 4\times10^{17}$cm^{-3}, N_{HOMO} = N_{LUMO} = 10^{20} cm^{-3}, ε_{rp}=ε_{rn}=2.0 and T=300K.

4. Conclusions

The dependences of the current density on the layer thickness, trap properties and operation voltage are numerically investigated, and following conclusions are arrived at: (1) For given values of reduced trap depth, total trap density and carrier mobility, there exists an optimum value for the thickness ratio of d_p/d, with which the maximal current density, and hence quantum efficiency and luminance, can be achieved; (2) The current density decreases quickly as the mean trap density increases, and an increase of one orders of magnitude of the mean trap density will result in a reduction of the current density for about 3 orders of magnitude; (3) The current density decreases exponentially with the mean reduced trap depth, and the greater the mean trap density, the steeper decreasing the current density.

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