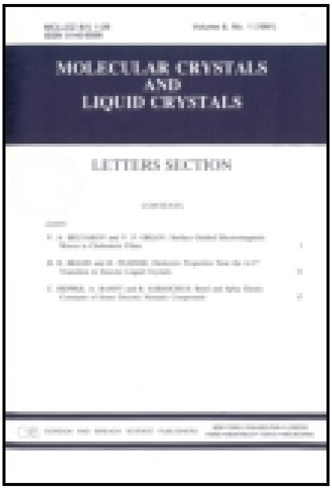

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Improvement of Current Efficiency at High Field Regime Via Description of Roll-off Characteristic in Model Device of OLEDs

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We demonstrated the effect of the field dependency of charge carrier mobility on roll-off characteristic of current efficiency. Field dependent factor in Poole-Frenkel model is controlled to describe charge balance of electron and hole concentration at high field. It is well established that roll-off characteristic is dependent upon mobility match which results in charge balance in EML. We exhibited the improvement of the roll-off characteristic of current efficiency and explained how charge balance is induced through this description.

Keywords Organic light emitting diodes; roll-off characteristics; current efficiency, device simulation

Introduction

Roll-off characteristic of current efficiency, efficacy and quantum efficiency results in severe performance degradation such as high power consumption and short lifetime [1–5].

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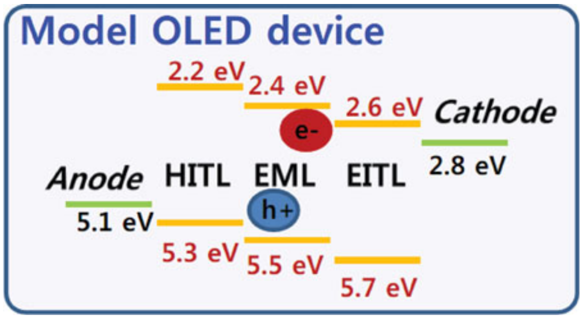

Figure 1. Schematic of the model OLED device structure and its energy level.

We explain how to improve the roll-off of current efficiency in PIN OLEDs(Organic Light Emitting Diodes) by using the concept of a charge balance between electron concentration and hole via device simulation. The charge balance has, in fact, not yet been handled quantavively through device simulation due to its impilicity. Physical parameters, therefore, such as a field dependency of electron mobility and hole, a zero-field mobility are applied with Poole-Frekel model to depict bulk properties of an emission layer in OLEDs for explicit parameter based modeling. While applied voltage has varied, the difference between electron and hole mobility could be diversed owing to the mismatch of the field dependency of electron carrier mobility and hole. This phenomenological behavior causes a charge imbalance which is suggested as one of the most critical factors to provoke a roll-off in many experiment [6–11]. Although those bulk properties have been of particular interest over decades, they had not yet been understood clearly in terms of charge balance. Thus, this result gives a guidance for a quantitative simulation methodology to figure out the relationship between the charge balance and the roll-off. An intuitive solution, in addition, can be drawn into an optimization of device structure and a design rule on materials sythesis to improve the performance in OLEDs.

Experimental

Figure 1 illustrates the schematic of the PIN OLEDs model device which has the injection barrier of 0.2 eV uniformly. This implies that only bulk property can be considered in model device since the injection barriers are set to the constant of 0.2 eV which enables to facilitate quasi-ohmic injection and variation in injection term can be readily neglected in this configuration [12,13]. The thickness of HITL (Hole injection and transport layer), EML (Emission layer) and EITL (Electron injection and transport layer) is 100 nm, 40 nm and 48 nm, respectively. The energy level of each layers are depicted in Figure 1. The work function of an anode and a cathode are set to −5.1 eV and −2.8 eV, respectively. Those values are somehow calibrated to satisfy the quasi-ohmic injection from electrodes to each organic layers. Basic parameters are set from generally used values in litteratures [14, 15]. We assume that excitons fully convert to light, which excludes non-radiative decay term. Exciton energy of singlet host and triplet host is 2.8 eV and 2.6 eV. Radiation from HITL and EITL is completely neglected thus we observe the physical event of light emission only in EML. This can render us to assume recombination zone emerges only in EML. The parameter set up enables to take into account match of electron and hole concentration in EML thus charge balance is solely treated as an effect to describe current efficiency.

Those equations are used to carry out finite element method based simulation for OLEDs by solving the Poisson equation as the following equation.

$$\frac{\partial F}{\partial x} = \frac{q}{\varepsilon \varepsilon_0} (p(x,t) + n(x,t))$$

Here, F is the electric field inside the OLED, q is the elementary charge, ε is the dielectric permittivity of the organic materials, ε_0 is the dielectric constant, p and n are the charge carrier concentrations for holes and electrons which include free and trapped charges, respectively.

$$\frac{\partial n_f(x,t)}{\partial t} = \frac{1}{q} \frac{\partial J_{nf}(x,t)}{\partial x} - R - T$$

Continuity equation for electron is expressed as the equation above whilst n_f is the charge carrier concentration of free electrons, J_{nf} is the electron current density, R is the recombination rate in between free and between free and trapped carriers) and T is the trapping rate for free carriers. Exciton density, therefore, can be formulated in the following equation while s is the exciton density, c is a factor due to spin statistics with 1/4 for singlet and 3/4 for triplet. D_S is the diffusion constant for excitons, τ_S is the exciton lifetime, and Q includes quenching terms for excitons in the case of quenching at contacts, free carriers or excitons [16].

$$\frac{\partial s(x,t)}{\partial t} = c \cdot R + D_s \frac{\partial s(x,t)}{\partial x} - \frac{s(x,t)}{\tau_s} - Q$$

Results and Discussion

We apply Poole-Frenkel (PF) mobility model in order to investigate field dependency of mobility in bulk semiconductor region while using the simulation tool of SimOLED which enables to solve a drift-diffusion equation based on 1-D finite element method [16]. PF mobility is shown in the following equation

$$\mu_e(E) = \mu_{0,e} \times \exp\left(\gamma_e \sqrt{E}\right)$$
$$\mu_h(E) = \mu_{0,h} \times \exp\left(\gamma_h \sqrt{E}\right)$$

where μ_0 is the zero-field mobility, γ is field dependent factor and E is electric field applied to the bulk semiconductor. Upon the equation, γ_e and γ_h are differently set to show diverse field dependency of electron and hole mobility. In fact, current efficiency of OLEDs decreases as applied field increases. Thus, we assume here that mobility of electron and hole has different field dependency in order to depict the situation of electron and hole charge imbalance at high field regime.

Figure 2 shows various field dependency of electron and hole mobility with zero-field mobility of 10^{-7} cm^2/Vs for electron and 10^{-6} cm^2/Vs for hole in EML, which is adapted from the property of p-type like EML. When electric field increases, electron and hole mobility augment according to equation just above, that is proportional exponentially to square root of electric field. In the sense of variance of field dependency, γ_h is controlled as a variable for mobility match at high field regime with fixed γ_e to 0.005. Field dependent factor of hole varies as 0.002, 0.005 and 0.01. The values are set in the standard of 0.005.

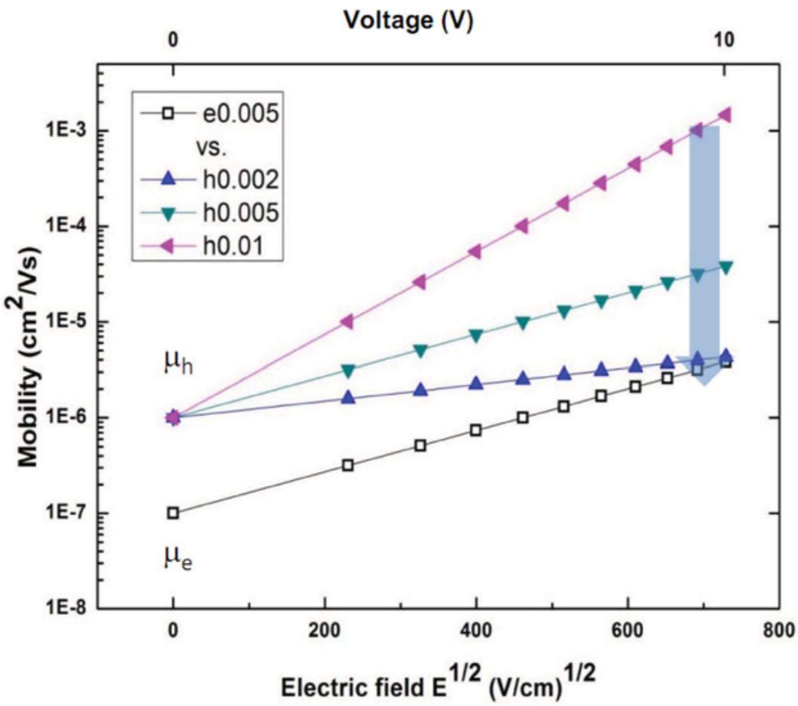

Figure 2. Field dependent Poole-Frenkel mobility of electron and hole carriers when γ of holes varies from 0.002 to 0.01 whilst γ of electrons stick to 0.005.

The smaller value than 0.005, that is 0.002, leads mobility of electron and hole to coincide at high field regime. This enables the match of electron and hole carrier concentration at EML. The larger value than 0.005, that is 0.01, leads mobility of electron and hole to split more. It shows the worse mismatch of electron and hole carrier concentration than the case when the field dependent factor of electron and hole mobility is same.

Figure 3 (a) and (b) depict current density-voltage, luminance-voltage characteristics. As shown in Figure 3 (a), while voltage increases, current density increases similarly even when field dependency differs. It is because current density is calculated from the sum of charge density in entire layer of device, so that fixation of charge carrier density in the device leads to similar current density in total region of device without the field dependency. Figure 3 (b) shows, however, luminance-voltage characteristic that behaves in a different way from Figure 3 (a). Luminance is dependent upon which layer electron and hole pair emerge and emit the light in. Therefore, the highest luminance represents when the field dependent factor is 0.002 with over 6000 nit. As the field dependent factor increases, luminance decreases. It goes down eventually to under 1000 nit when the field dependent factor reaches 0.01, that is the most mismatched electron and hole mobility in EML is expected.

Figure 4 describes current efficiency roll-off characteristic when luminance increases. In fact, current efficiency, that is the ratio of luminance to output current density, can be one of the decision factors that determine the stability of OLEDs at device operation regime. Roll-off ratio is defined as current efficiency when luminance is 4000 nit to current efficiency when luminance is max in this simulation. The case of field dependency with 0.01

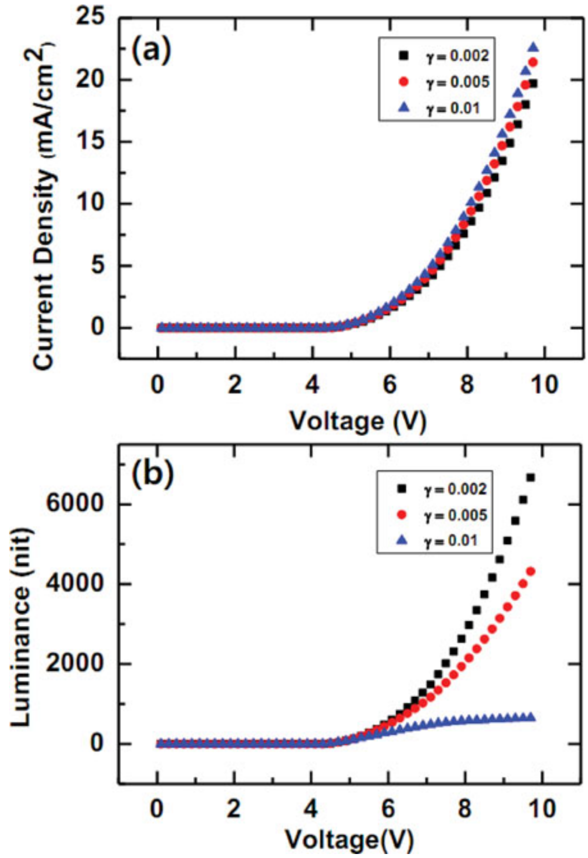

Figure 3. Relationship of (a) current density-voltage and (b) luminance-voltage.

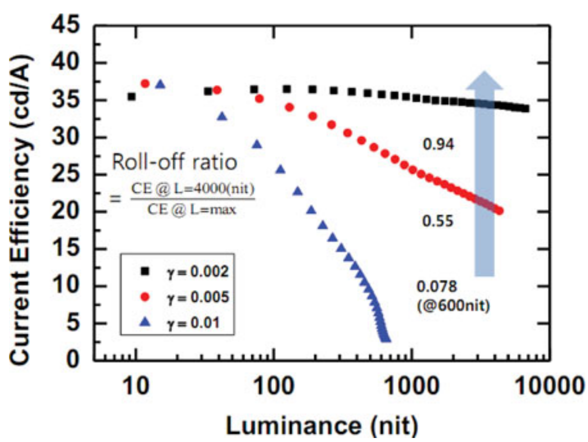

Figure 4. Improved roll-off characteristic of current efficiency which is defined as luminance at 4000 nit over luminance at maximum. When γ of hole is 0.01, roll-off is defined as luminance at 600 nit over luminance at maximum due to its limited luminance.

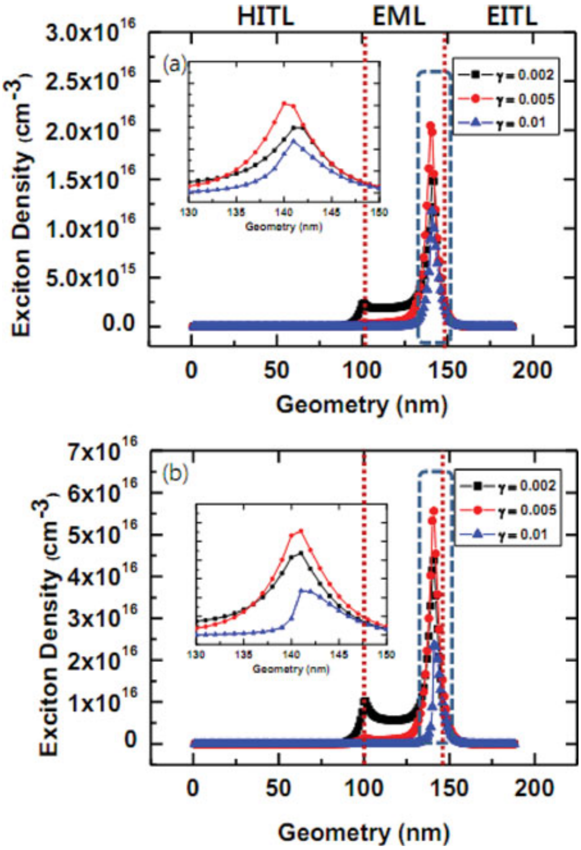

Figure 5. Exciton density profiles differ due to the change of charge balance (a) at 5.7 V and (b) at 9.7 V.

emits smaller than 1000 nit of light so that the ratio is defined as current efficiency when luminance is 600 nit to current efficiency when luminance is max in this case. The roll-off ratio is varied from 0.078 to 0.94 when the field dependent factor is changed from 0.01 to 0.002, that is, the variance of mobility field dependency improves roll-off characteristic by over 12 times.

It is attributed from electron and hole concentration balance in EML where happens light emission mostly [17]. Figure 5 shows the exciton density profiles in the geometry of OLEDs which can be expressed as exciton concentration in cm^3. Figure 5 (a) and (b) show the change of exciton density profile at 5.7 V and at 9.7 V which represent the low fand high field regime, respectively. EML spans from 100 nm to 140 nm with the thickness of 40 nm. The figure shows only triplet exciton because its density is over two order of magnitude higher than singlet case. At low field regime, most of excitons exist in EML independent of field dependency as shown in Figure 5 (a). Roll-off characteristic at low field regime, therefore, is not as severe as the one at high field regime. On the contrary, exciton density profile is dependent upon the field dependency of hole mobility at high field regime as shown in Figure 5 (b). Exciton density is concentrated at the interface between EML and EITL and larger portion of excitons exist in EITL in Figure 5 (b) than at low field regime in Figure 5 (a) for the case of field dependent factor of 0.01 even though total exciton density increases twice at high field regime. The insets of Figure 5 (a) and (b) show explicitly the difference of exciton density profile with the field dependent factor of 0.01, that is, charge carrier concentration is intentionally imbalanced at high field regime through mobility field dependency as depicted in Figure 2.

Conclusion

The effect of charge balance on roll-off characteristic has been dealt with in terms of field dependency of electron and hole mobility with respect to electric field. When field dependent factor of hole mobility is smaller enough than the one of electron, with γ_{h} of 0.002 and γ_{e} of 0.01, mobility matches at 10 V so that charge carrier concentration is well balanced. This implies that charge balance leads the improvement of roll-off characteristic of current efficiency. It is evidently shown in the exciton density profile in Figure 5 that the amount of excitons out of EML can occur the roll-off characteristic of current efficiency at high field regime. Field dependent factor is used as a control factor to describe field dependent charge imbalance in Poole-Frenkel mobility model.

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