K-7-1 (Invited)

Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp918-919

Exciplex Forming Co-Hosts as a Platform for OLEDs with Ultimate Efficiency

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Abstract

We present highly efficient OLEDs using various exciplex forming co-hosts and phosphorescent and fluorescent dyes with horizontally oriented transition dipole moments (TDM) and high photoluminescence quantum yield (q_{PL}), including blue (EQE of 30%), green (EQE of 32%), orange (EQE of 32%) and red (EQE of 36%), white (EQE of 28.8%) and fluorescent green (EQE of 30%) OLEDs. The theoretical prediction based on the classical dipole model agrees very well with the experimental data, validating the optical model used for the prediction of the EQEs. Based on the validation, we offer a universal plot of maximum efficiency of OLEDs achievable with different values of PLQY and orientation of TDM without fabricating devices. The optical analysis indicates that OLEDs with EQE higher than 40% can be realized without any extra light extraction layers, if phosphorescent dyes with q_{PL} and horizontal portion of TDM over 95% are used..

1. Introduction

Maximum external quantum efficiency of OLEDs is known to be about 25~30% without any extra light extraction layer if emitting dipoles are randomly oriented. However, an emitter with a horizontal transition dipole moment (TDM) results in much higher outcoupling efficiency than the vertically aligned dipole as demonstrated in polymers and vacuum evaporated organic molecules. Recently, not only fluorescent molecules but also some phosphorescent dyes are reported to have preferred horizontal dipoles where high EQE over 30% is expected. Unfortunately few experimental data have demonstrated the potential of horizontally oriented phosphorescent dyes to get high efficiencies over 30% until very recent years. Demonstration of high efficiency OLEDs over 30% requires a device structure with perfect electrical balance without electrical loss and a phosphorescent dye with high photoluminescence quantum yield (q_{PL}) and TDM oriented in the horizontal direction.

In this talk, we present highly efficient OLEDs using various exciplex forming co-hosts and phosphorescent and fluorescent dyes with horizontally oriented TDM and high PLQY, which include phosphorescent blue (EQE of 30%), green (EQE of 32%), orange (EQE of 32%), red (EQE of 36%) and white (EQE of 28.8%), and fluorescent green (EQE of 30%) OLEDs. The theoretical prediction based on the classical dipole model under the assumption of little electrical loss agrees very well with the experimental data, validating the optical model used for the prediction of the EQEs.. The optical analysis indicates that OLEDs with EQE higher than 40% can be realized without any extra light extraction layers, if phosphorescent dyes with PLQY and horizontal portion of TDM over 95% are used. [1-10]

2. Simulation of External Quantum Efficiency [2]

The EQE of an OLED has been expressed by the following equation:

$$\eta_{EQE} = \gamma \times \eta_{S/T} \times q_{PL} \times \eta_{out} \qquad (1)$$

where γ is the charge balance factor, $\eta_{S/T}$ is the singlet-triplet factor ($\eta_{S/T}$ =0.25 for fluorescent, $\eta_{S/T}$ =1 for phosphorescent emitter), and η_{out} is the outcoupling efficiency of the emitted light. However, the quantum efficiency of an emitter in a micro-cavity structure is influenced by the orientation of the emitter, the local electric field at the dipole position and the proximity to a metal layer. The η_{out} is influenced not only by the device structure but also by the orientation of emitting dipoles so that the EQE must be modified as follows.

$$\eta_{EQE} = \gamma \times \eta_{S/T} \times q_{eff}(q_{PL}, \Theta, \Gamma) \times \eta_{out}(\Theta, \Gamma) \quad (2)$$

where q_{eff} is the effective quantum yield that describes the probability of radiative exciton decay in an optical cavity structure (i.e. the Purcell effect), which is generally depending on q_{PL}, the orientation factor (Θ, the ratio of the horizontal dipoles to total dipoles), and the geometric factor of the device (Γ) including the device structure and the location of the emission zone in the device. In a similar manner, η_{out} is influenced by Θ and Γ. The γ value is often assumed to be unity in state-of-the-art OLEDs, however, this value is not a constant but a fitting parameter in this study. With separately measured values of q_{PL} and Θ, and using known information of the device structure, we can now calculate q_{eff} and η_{out} from a classical dipole model and then fit to the experimentally obtained EQE to extract γ.

3. Results and Discussion [2]

The device under investigation has a simple structure of glass/ITO (70 nm)/TAPC (x nm)/TCTA (10 nm)/TCTA:B3PYMPM:$Ir(ppy)_2(acac)$ (1:1 of molar ratio and 8 wt.%) (30 nm)/B3PYMPM (40 nm)/Al (100 nm). We used the mixed co-host of TCTA:B3PYMPM as the host of the phosphorescent dopant to take advantage of its exciplex-forming characteristics The thickness of the TAPC layer was set as a parameter and varied from 40 to 100 nm.

The maximum EQE of 30.2% was obtained with the 80 nm-thick TAPC layer. Optical simulation of the EQE of the devices was performed using the experimentally obtained values of q_{PL} =0.94 and Θ=0.77±0.02. The experimental results are very well described by the simulated results as shown in Fig. 1 under the condition of γ=1, indicating that the electrical loss is indeed negligible. In other words, the injected electrons and holes into the EML of the OLEDs efficiently recombine to form excitons. The excellent match between the experimental and the simulation results clearly indicates that the optical simulation describes the maximum achievable EQE under the known values of q_{PL} and Θ when the device structure is optimized electrically and optically. This fact implies that we can predict the maximum EQE achievable with a certain emitting dye in a host by just measuring q_{PL} and Θ on a neat film of the EML on glass without the need for fabrication of full OLED devices.

Based on this idea, we extend the simulation to calculate the maximum achievable EQEs as functions of q_{PL} and Θ. The corresponding simulation results are shown in Fig. 2 as a contour plot. We used the structure shown in Fig.1a with the optimized thickness of the TAPC layer (75 nm) for the simulation. The maximum efficiency increases as q_{PL} and Θ approach 1 as expected. Surprisingly, a maximum EQE of 46% can be achieved in normal ITO based bottom emitting OLEDs without any extra outcoupling layers using a phosphorescent dye with q_{PL} =1 and Θ = 1. Practically over 40% EQE is possible with q_{PL} = 0.95 and Θ = 0.95. In contrast, the maximum EQE of the OLED with isotropically oriented phosphorescent dyes is much lower (~ 25%).

We fabricated OLEDs with various colors using similar device structures doped with various phosphorescent dyes

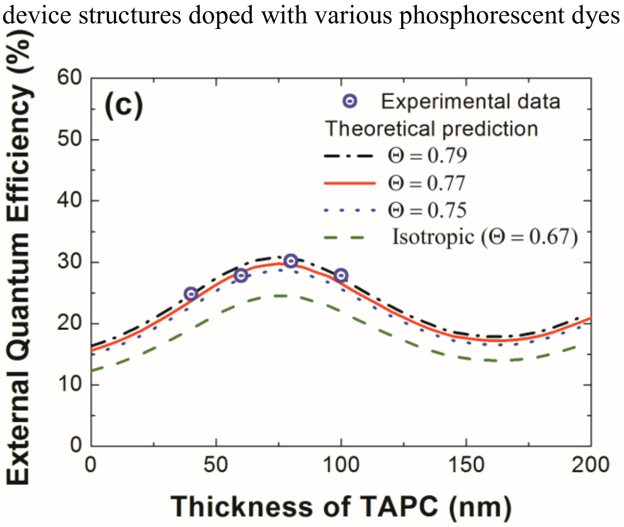

Fig.1 Experimental EQEs (circles) are compared with simulated EQEs with different orientation factors of dipoles.

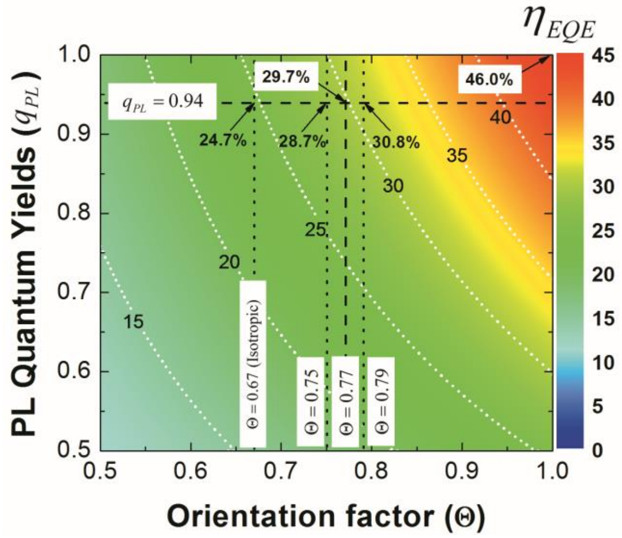

Fig. 2. Contour plot of the simulation result of maximum EQE as functions of q_{PL} and Θ for green OLEDs.

The results are summarized in Table 1. All the experimental results well match with the theoretical predictions, reaching to an unprecedentedly high EQE of 35.6% for a red OLED. These results clearly demonstrate that (1) the exciplex forming co-host systems can be used as a platform for OLEDs with ultimate efficiencies without electrical loss, and (2) a maximum EQE of 46% can be achieved in normal ITO based bottom emitting OLEDs without any extra outcoupling layers using a phosphorescent dye with q_{PL} =1 and Θ = 1.

Table 1. EQEs of OLEDs with different colors

color	q_{PL} (%)	Θ (%)	EQE(exp) (%)	EQE(cal) (%)
Green	96	78	32.3	32
red	96	82	35.6	34.9
Blue	100	76	29.5	29.9
Green Fluorescence	97	73	29.6	29.2

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