Journal of Photochemistry and Photobiology C: Photochemistry Reviews 11 (2010) 133–156

Contents lists available at ScienceDirect

Journal of Photochemistry and Photobiology C: Photochemistry Reviews

journal homepage: www.elsevier.com/locate/jphotochemrev

Invited review

Recent progress and current challenges in phosphorescent white organic light-emitting diodes (WOLEDs)

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ARTICLE INFO

Article history:
Received 23 November 2010
Accepted 11 January 2011
Available online 18 January 2011

Keywords:
White organic light-emitting diodes
Phosphors
R-G-B primary colors
B-O complementary colors
Excimer/exciplex

ABSTRACT

White organic light-emitting diodes (WOLEDs) offer a promising avenue to developing future energy-saving solid-state lighting sources because of their intrinsic characters such as low driving voltages, high brightness and efficiency, large area, etc. While commercialization of WOLEDs has attracted tremendous interest in both academic and industrial communities, the discovery of highly efficient phosphors opens up a good channel to meet this target. With the goal towards practical application, many design strategies, including new materials synthesis, judicious design of device configuration, wise management of charges/excitons in different active layers, development of sophisticated and low cost fabrication procedures, etc. have been put forward to achieve high efficiency, good white color stability and quality. In this review, the most recent progress and achievements in various research aspects of the phosphorescent WOLED is presented. Practical applications are enumerated and illustrated by specific examples. The major advances, ongoing challenges and future perspectives of this research frontier are also critically discussed. The present work provides valuable clues to the specialists in the field to develop new routes for future research development of WOLEDs.

Contents

1. Introduction 134
2. The basics of WOLEDs 134
   2.1. Efficiency 134
   2.2. Quality of white light 135
   2.3. Generation of white light from WOLEDs 135
3. WOLEDs with phosphorescent emitters 136
   3.1. All-phosphorescent WOLEDs 136
      3.1.1. WOLEDs from R-G-B primary colors 136
      3.1.2. WOLEDs from B-O complementary colors 142
   3.2. WOLEDs from fluorescent/phosphorescent (F/P) hybrids 146
      3.2.1. F/P hybrid WOLEDs with small molecular emitters 147
      3.2.2. F/P hybrid WOLEDs with single polymeric emitters 149
   3.3. WOLEDs based on excimer/exciplex emission from phosphors 150
4. Concluding remarks 155
   Acknowledgements 155
   References 155

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doi:10.1016/j.jphotochemrev.2011.01.001

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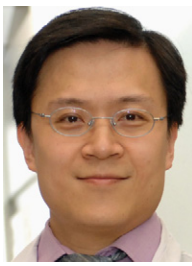

Wai-Yeung Wong was born in Hong Kong, and graduated with both B.Sc.(Hons.) (1992) and Ph.D. (1995) degrees (Ph.D. supervisor: Prof. Wing-Tak Wong) from the University of Hong Kong. After his postdoctoral work at Texas A&M University in 1996 with Prof. F. Albert Cotton, he worked in the groups of Profs. The Lord Jack Lewis (FRS) and Paul R. Raithby at the University of Cambridge in 1997 as a Croucher Research Fellow. He joined Hong Kong Baptist University as an Assistant Professor in 1998 and is currently a Chair Professor in Chemistry. His research focuses on synthetic inorganic and organometallic chemistry and structural chemistry, with special emphasis on developing metallopolymers and metallophosphors with energy functions and photofunctional properties. He has a distinguished publication record of over 330 scientific articles. He holds the guest professorship of eight institutions in Mainland China. He is also the recipient of the Chemistry of the Transition Metals Award by the Royal Society of Chemistry in 2010, and has won the Croucher Senior Research Fellowship and two Asian Core Program Lectureship Awards in 2009. He is currently a co-editor of the Central European Journal of Chemistry and serves on the editorial/international advisory boards of Macromolecular Rapid Communications, Macromolecular Chemistry & Physics, Dalton Transactions, Journal of Organometallic Chemistry, Comments on Inorganic Chemistry, Current Organic Chemistry, Macromolecular Research, Journal of Inorganic & Organometallic Polymers and Materials and Journal of Cluster Science.

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1. Introduction

After the milestone work of C.W. Tang in the field of electroluminescence [1], organic light-emitting diodes (OLEDs) are always attracting high research enthusiasm from both scientific and industrial communities for their thin-film, high-contrast, light-weight, fast-response, wide-view-angle and low-power attributes, and they have been regarded as one of the best flat panel display technologies that are capable of meeting the most stringent demand of future display applications [2–20]. Besides the great potential in display industries, another attractive application associated with OLEDs as the next generation solid-state lighting sources with the favorable energy-saving traits would lead to the prosperity of OLED investigation [21–25]. OLEDs emitting white light had been realized ca. 15 years ago by Kido and coworkers via mixing three fluorescent dyes (blue, green and orange) into a single emission layer (EML). White light with a broad spectrum was produced [26–33]. Furthermore, high brightness (3400 cd m^{-2}) can be achieved at low driving voltage (ca. 14 V). All these unique features would render white organic light-emitting diodes (WOLEDs) ideal candidates for future energy-saving lighting sources, since 90% of the consumed power by a traditional incandescent bulb is actually converted into heat. Lighting occupies a significant part of the world's energy consumption, with a large share still consumed by inefficient incandescent lamps [34]. So, the guest for more efficient and environmentally friendly solutions to the impending world energy shortage has stimulated extensive research interest for WOLEDs as new generation ambient lighting sources.

At the early stage of WOLED research, fluorescent (singlet) emitters are usually adopted to produce white light emission from the as prepared devices [35–46]. However, the traditional singlet-emitting (fluorescent) chromophores would favor a 3:1 ratio of the non-emissive triplet states over singlet states according to the quantum spin statistics prediction for the free charge-carriers, which severely limits the device efficiency and has brought about the bottle-neck problem of WOLEDs [47–54]. Fortunately, the discovery of phosphorescent (triplet) emitters had made revolutionary progress in improving the device efficiencies of WOLEDs since they can harness both of the singlet and triplet excited states for emission at room temperature [3]. Typically, it was the highly efficient phosphors that made WOLEDs possible as the thin-film solid-state lighting sources, in which efficiency is one of the most important parameters for consideration. To date, these phosphorescent emitters are mainly derived from complexes of the third-row transition metals (e.g. Re^{I}, Os^{II}, Ir^{III} and Pt^{II}) for their high spin-orbit coupling constants that are capable of facilitating the triplet emission even at room temperature [55–64]. The unique photophysical properties associated with Ir^{III} and Pt^{II} ppy-type (Hppy = 2-phenylpyridine) complexes, such as tunable emission color, high phosphorescent quantum yield (Φ_p) and relatively short triplet lifetime (τ_p), etc., would definitely put them in a prominent position for developing low-cost lighting sources. All of these advantages have stimulated researchers from both academic and industrial organizations to develop WOLEDs. Recently, WOLEDs with efficiency of 120 lm W^{-1} have been realized with highly efficient phosphors under laboratory conditions and the efficiency is even higher than that of fluorescent tubes widely in use nowadays [65]. With all these efforts, the first products have been commercialized in the market. In this review, we report the recent progress in the exciting field of WOLEDs, especially those involving the phosphorescent device components.

2. The basics of WOLEDs

2.1. *Efficiency*

External quantum efficiency (EQE, η_{ext}), current efficiency (CE, η_C) and power efficiency (PE, η_P) are the common parameters employed to characterize the performance of WOLEDs. EQE is defined as the total number of photons emitted out of the device by consuming per electron–hole pair injected into the devices. It can be defined as follows:

$$\eta_{ext} = \eta_{in}\eta_{ph} = \gamma_{e-h}\eta_{s-p}\Phi_i\eta_{ph}$$

where η_{in} is the internal quantum efficiency (IQE) that is defined as the total number of photons generated inside the device per electron-hole pair injected, η_{ph} is the out-coupling efficiency, γ_{e-h} is the ratio of electrons to holes (or vice versa) injected from opposite electrodes to keep $\gamma_{e-h} \leq 1$, η_{s-p} is the fraction of the emissive excitons, which is 0.25 for fluorescent emitter and 1.0 for the phosphorescent counterpart, Φ_i is the intrinsic quantum efficiency for radiative decay consisting of both phosphorescence and fluorescence.

The η_C is generally employed to characterize the efficiency of device which can be "evaluated" by the naked eyes. So, it is also called luminous efficiency (η_L) which is defined as follows:

$$\eta_C = \frac{AL}{J}$$