Research Article **Open Access**

Marc Lepeltier, Frédéric Dumur*, Guillaume Wantz, Denis Bertin, Didier Gigmes, and Cédric R. Mayer

White and Saturated Blue Phosphorescent OLED based on the Non-Emissive Homoleptic Complex $Ir(ppz)_3$ as single active material

Abstract: The well-known homoleptic iridium (III) complex $Ir(ppz)_3$ which is only emissive in solution at low temperature has been investigated as dopant in a $p-i$ stacked OLED architecture. Interestingly, while using this phosphor as a single emitter, a white OLED was obtained. Emission colour was determined as being concentration and thickness-dependent.

Keywords: OLEDs, iridium, photoluminescence, electroluminescence, metal complex

Marc Lepeltier: Institut Lavoisier de Versailles ILV – UMR CNRS 8180, Université de Versailles Saint-Quentin en Yvelines, 45 avenue des Etats Unis, 78035 Versailles, France
***Corresponding Author: Frédéric Dumur:** Aix-Marseille Université, CNRS, Institut de Chimie Radicalaire, UMR 7273, F-13397 Marseille, France, E-mail: frederic.dumur@univ-amu.fr
***Corresponding Author: Frédéric Dumur:** Univ. Bordeaux, IMS, UMR 5218, F-33400 Talence, France
***Corresponding Author: Frédéric Dumur:** CNRS, IMS, UMR 5218, F-33400 Talence, France
Guillaume Wantz: Univ. Bordeaux, IMS, UMR 5218, F-33400 Talence, France, E-mail: guillaume.wantz@ims-bordeaux.fr
Guillaume Wantz: CNRS, IMS, UMR 5218, F-33400 Talence, France
Denis Bertin, Didier Gigmes: Aix-Marseille Université, CNRS, Institut de Chimie Radicalaire, UMR 7273, F-13397 Marseille, France
Cédric R. Mayer: Laboratoire d'Ingénierie des Systčmes de Versailles LISV – EA 4048, Université de Versailles Saint Quentin en Yvelines, 10/12 avenue de l'Europe, 78140 Vélizy, France, E-mail: cmayer@lisv.uvsq.fr

1 Introduction

During the past decade, white organic light-emitting diodes (WOLEDs) have attracted a great attention as potential candidates for next generation displays, signage and solid-state lighting sources [1, 2]. Over the years, several strategies have been developed to produce white light: mixture of the three primary Red Green Blue (RGB) colors [3, 4] within a single emitting layer or segregation of the three emitters into adjacent layers, combination of two complementary colors [5, 6]. However, serious problems are evidenced in multilayer white OLEDs such as the reproducibility of the device preparation, the variation of the Commission Internationale de l'Eclairage (CIE) coordinates as a function of the driving voltage or the unequal aging of the different emitters conducing to an emission change over the time. Conversely, WOLEDs incorporating a single emitter are quite few [7–12]. In this case, a higher stability of the emission color with the driving voltage and enhanced lifetimes are demonstrated. Parallel to this research field, blue OLEDs is an active research field from the organic or organometallic point of view [13, 14]. Yet blue phosphors are of crucial importance in various applications such as full-color flat-panel displays and solid state lightings, the number of blue emitters at disposal is still behind the others and new complexes are thus still actively researched. Notably, deep blue PhOLEDs are hardly attainable as a result of the requirement of designing wide bandgap materials that often exhibit shallow LUMO levels rendering an efficient electron injection difficult [15–23]. A red-shift of the electroluminescence (EL) emission wavelength compared to the photoluminescence (PL) in solution is also often observed due to solid-state aggregation and use of complexes with a PL in solution close to the near UV region is thus required to get a good color purity. Based on the wide range of potential applications that can have deep-blue OLEDs, investigating new families of complexes is a pressing concern. Among all phosphorescent emitters under investigation, iridium (III) complexes are without contest among the most widely studied transition metal complexes: as neutral emitters [24] or as soft salts [25–27] for the design of OLEDs or as ionic complexes [28–30] for the design of Light-Emitting Electrochemical Cells (LECs). As main advantage over the other transition metal complexes, relatively short excited state lifetime enables to efficiently minimize the triplet-triplet (T-T) annihilation [31, 32]. So far, metal complexes that are nearly non-emissive at room temperature but revealing a decent emission at 77K have only been scarcely in-

vestigated as emitters for OLEDs [33]. Emitters are often selected for their high photoluminescence quantum yield in solution and in the solid state. In the case of complexes with low quantum yields of luminescence, moderate performances are already anticipated but interesting colors can be obtained. More generally and to the best of our knowledge, only two almost non-emissive platinum (Φ <0.02 and Φ = 0.03) [34–36] and iridium complexes [37, 38] (Φ = 0.0046 and Φ = 0.1) have been incorporated in OLEDs. Concerning iridium complexes that suffer from an extremely low emission quantum yield in both fluid and solid states at RT, $Ir(ppz)_3$ with ppz = 1-phenylpyrazole is a well-known blue phosphor [39, 40]. Notably, $Ir(ppz)_3$ has already been incorporated in devices acting as a hole and excitons blocking layer [41–44]. However, this complex has never been used as emitter for OLEDs. Herein, we report on OLEDs prepared with $Ir(ppz)_3$ as a single-dopant. As anticipated by using a deep-blue dopant, blue-OLEDs were obtained. However, a WOLED was obtained at 5.1 wt% doping concentration.

2 Experimental details

2.1 General Informations

The complex $Ir(ppz)_3$ was synthesized by following a literature procedure without modification and obtained with similar yield [39].

2.2 OLEDs fabrication and measurements

OLEDs were fabricated onto cleaned indium tin oxide (ITO) glass substrates with sheet resistance of 10 – 12 Ω/cm^2. Prior to organic layer deposition, the ITO substrates were successively washed with acetone, ethanol and isopropanol in ultrasonic bath for 15 min., and finally exposed to UV-ozone 20 min before loaded into a deposition chamber. All materials used for the device fabrication were purchased from Lumtec with the best purity available and used as received. Organic layers were then sequentially deposited onto the ITO substrate at a rate of 2 – 4 Å/s and a pressure below 1×10^{-6} mbar. Aluminum cathode was formed with a shadow mask by thermal evaporation under secondary vacuum. Device structure is the following: ITO was used as a transparent anode electrode, *N,N,N',N'*-tetra*kis*4-methoxyphenylbenzidine (MeOTPD) doped with 2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane (F_4-TCNQ) as a hole injecting material, MeOTPD as a hole transporting layer, 4,4',4"-tris(*N*-carbazolyl)triphenyl-amine (TCTA) doped with iridium as the light-emitting material, 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP) as a hole blocking material, 1,3,5-tris(N-phenylbenzimidizol-2-yl)benzene (TPBI) as an electron transporting material, lithium fluoride (LiF) as an electron injecting material, and Al as a cathode electrode material. Current density–voltage–luminescence (J–V–L) characteristics of LECs were measured with a Keithley 4200 semiconductor analysor coupled with a Hamamatsu Light sensor calibrated with a Minolta CS-100 luminancemeter. The EL spectra were collected with an Ocean Optics HR2000 Spectrometer. Chromatic Coordinates were calculated from the EL spectra and reported following the CIE-1964 chromaticity diagram. From the electrode deposition step, devices were stored and characterized in nitrogen filled gloveboxes (O_2 and H_2O < 0.1 ppm) without encapsulation.

3 Results and discussion

Electroluminescence (EL) performance of $Ir(ppz)_3$ was investigated in a typical doping device structure of ITO/MeOTPD:F_4-TCNQ (7.5 wt%, 100 nm)/MeOTPD (15 nm)/TCTA:Ir (50 nm)/BCP (15 nm)/TPBI (100 nm)/LiF (1 nm)/Al. MeOTPD:F_4-TCNQ was used as a hole-injection layer, MeOTPD acts as a hole-transporting layer, TCTA:Ir is the emissive layer, BCP and TPBI are employed as hole-blocking layer and electron-transporting layer, respectively. OLEDs were prepared by vapor deposition technology and characterized without encapsulation in a nitrogen glovebox. Three doping concentrations were investigated i.e. 3, 5.1 and 11.4 wt%. Surprisingly, a WOLED was obtained at the doping concentration of 5.1 wt% whereas the two other doping concentrations provided blue devices, as anticipated when a saturated deep blue dopant is used. Characteristics of luminance-voltage (L-V) of the three OLEDs are shown in Figure 1 and summarized in Table 1. The turn-on voltages defined at a luminance of ~ 1 $cd.m^{-2}$ were 3.9, 7.2 and 4.0 V respectively. Interestingly, the highest turn-on voltage was observed for the WOLED. All devices displayed moderated EL performances with maximum brightnesses ranging from 250 to 347 $cd.m^{-2}$. These results are directly related to the low PL quantum yield of this complex at RT. EL spectra of the three EL devices with different doping concentrations from 3 to 11.4 wt% are shown in Figure 2. At low dopant concentration of 3 wt%, a saturated blue EL with emission maximum at 420 nm was obtained. In particular, the EL spec-

Table 1. Device performances of PhOLEDs. Max and CIE represent maximum and Commission Internationale de l'Eclairage, respectively.

Device	V_{ON} (V)[a]	Max η_c (cd.A^{-1})	Max η_p (lm.W^{-1})	CIE coordinates	Max brightness (cd.m^{-2})[b]	λ_{EL} (nm)[c]
3 wt%	3.9	0.048	0.026	0.17, 0.11	347 (7.9 V)	420
5.1 wt%	7.2	1.17	0.36	0.29, 0.33	250 (12V)	(422), 522
5.1 wt%	5.1	0.016	0.0086	0.17, 0.12	62 (7 V)	431
11.4 wt%	4.0	0.05	0.022	0.19, 0.18	256 (8.8 V)	427

[a] Recorded at 1 cd.m^{-2}. [b] Value in brackets corresponds to the voltage at which the luminance was observed. [c] Value in brackets correspond to a shoulder.

trum matches the photoluminescence (PL) spectrum of $Ir(ppz)_3$ at low temperature. CIE coordinates of the blue light (0.17, 0.11) are close to the blue color of the National Television Standards Committee (NTSC) (1979) standard for the cathode ray tube (CRT) (0.14, 0.08) [45–47]. As revealed by the EL spectrum, EL emission comes directly from the triplet excited states of the iridium (III) complex as the EL spectrum coincides the PL spectrum. This indicates a complete energy transfer between host and dopant in the TCTA single-dopant emitting system. By increasing the dopant concentration, a complete change of the EL spectrum was observed and a white OLED was obtained. The broad emission covers the whole visible region and ranges from 400 to 800 nm. One main emission peak at 512 nm with a shoulder peak at 422 nm are observed. CIE coordinates of the $Ir(ppz)_3$-doped device (0.29, 0.33) are close to the CIE coordinates (0.33, 0.33) of a pure white emission. As specificity, white OLEDs exhibited a higher turn-on voltage and required a higher driving voltage than other devices. Broadening of the EL emission can be confidently assigned to contributions from the other layers even if the high-energy emission at 422 nm of the complex is still detectable. Upon increasing the dopant concentration to 11.4 wt%, a slight shift of the saturated blue emission (427 nm) was observed compared to that obtained for the device at 3 wt% (420 nm). A frequent problem encountered with the white emission of sandwich structure is the bias-dependent color variation, this variation being attributed to a shift of the recombination zone as a result of the difference of hole and electron carrier mobility of each material [48, 49]. While varying the applied voltage, almost no color change was observed on the WOLED, as evidenced in the Figure 3. Finally, overall thickness of the device was investigated as another factor potentially influencing the emission color. Increase of the thickness can also shift the recombination zone by the necessity of applying higher driving voltages to get light and thus modify the emission color. Thinner devices were only studied in the case of the white OLED in the following configuration: ITO/MeOTPD:F_4-TCNQ (7.5 wt%, 100 nm)/MeOTPD (15 nm)/TCTA:Ir (5.1 wt%, 40 nm)/BCP (10 nm)/TPBI (50 nm)/LiF (1 nm)/Al. While decreasing the overall thickness to 65 nm and keeping the dopant concentration constant, the color radically changed from white to blue clearly indicating the shift of the recombination zone in the case of the thicker devices. For the thin devices, turn-on voltage and driving voltages close to that previously obtained for the former blue OLEDs were reached. When the thickness is increased, higher bias are required and a shift of the recombination zone at the interface between the emissive layer and MeOTPD is observed, as previously reported [50, 51] (See Figure 4).

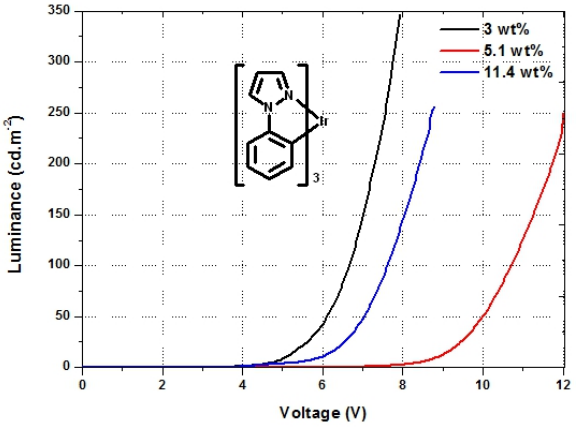

Fig. 1. Luminance characteristics at different doping concentrations.

4 Conclusions

A non-emissive iridium complex at room temperature has been investigated as dopant for stacked devices. Interestingly, while modifying the dopant concentration or the thickness of the device, saturated blue or white OLEDs

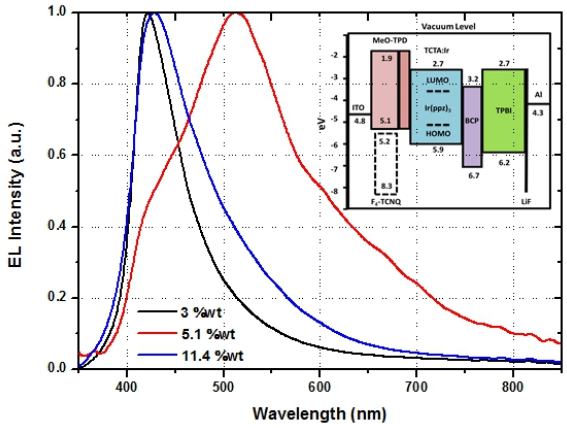

Fig. 2. EL spectra of devices upon various dopant concentrations from 3 wt% to 11.4 wt%. Inset: energy-level diagram of EL devices.

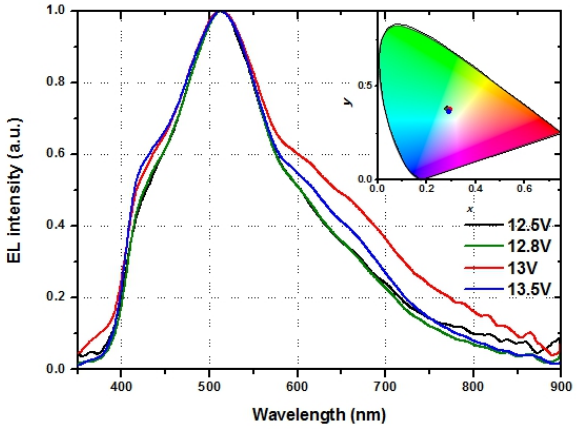

Fig. 3. Variation of the EL spectra with the applied voltage at a doping concentration of 5.1 wt%.

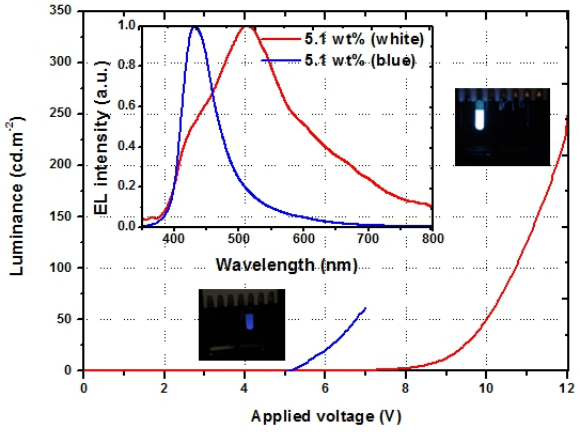

Fig. 4. EL characteristics of the thin and thick devices at constant doping concentration. inset : color variation with the device thickness.

could be obtained using a single-emitting material. As a result of the use of a single dopant, an excellent EL stability with the applied voltage was evidenced and an interesting color purity could be obtained for both the blue and white OLEDs. Even if the performance presented in this article are moderate compared to what reported with other iridium complexes and directly related to the low PL quantum yield of the complex at RT, these results render this phosphor as a promising scaffold for generating new emitters with higher PL quantum yields and broad emissions. Indeed, only few derivatives of this well-known $Ir(ppz)_3$ have been synthesized to date and the unique strategy to improve the PL quantum yield of this family of complex while blue-shifting the emission is to introduce electron-withdrawing groups on the aromatic rings.

Acknowledgement: The authors thank the CNRS, Aix-Marseille University, the Institut Carnot STAR and Continental Automotive Rambouillet for financial supports. Authors are thankful to Sokha Khiev for his technical assistance.

References

[1] C. W. Tang and S. A. Van Slyke, Organic electroluminescent diodes, Appl. Phys. Lett. 51, 1987, 913.

[2] J. Kalinowski, M. Cocchi, D. Virgili, V. Fattori and J. A. Gareth Willams, Mixing of Excimer and Exciplex Emission: A New Way to Improve White Light Emitting Organic Electrophosphorescent Diodes, Adv. Mater. 19, 2007, 4000.

[3] M. Meng, Y.-H. Kim, S.-Y. Lee, W. Song, H.-J. Yang, G.-W. Kim, B.-M. Lee, H.-H. Yu, C.-K. Lee and W. Y. Kim, Three primary-colored WOLED using MADN as host material, Nanosci. Nanotechnol. Lett. 3, 2011, 131.

[4] B. W. d'Andrade and S. R. Forrest, White organic light-emitting devices for solid-state lighting, Adv. Mater. 16, 2004, 1585.

[5] C.-L. Ho, L.-C. Chi, W.-Y. Hung, W.-J. Chen, Y.-C. Lin, H. Wu, E. Mondal, G.-J. Zhou, K.-T. Wong and W.-Y. Wong, Carbazole-based coplanar molecule (CmInF) as a universal host for multi-color electrophosphorescent devices, J. Mater. Chem. 22, 2012, 215.

[6] T.-H. Han, Y. Lee, M.-R. Choi, S.-H. Woo, S.-H. Bae, B. H. Hong, J.-H. Ahn and T.-W. Lee, Extremely efficient flexible organic light-emitting diodes with modified graphene anode, Nat. Photonics. 6, 2012, 105.

[7] Y. W. Ko, C.-H. Chung, J. H. Lee, Y.-H. Kim, C.-Y. Sohn, B.-C. Kim, C.-S. Hwang, Y.-H. Song, J. Lim, Y.-J. Ahn, G.-W. Kang, N. Lee and C. Lee, Efficient white organic light emission by single emitting layer, Thin Solid Films 426, 2003, 246.

[8] Y. Wang, Y. Liu, X. Li, H. Qi, M. Zhu, L. Wang, G. Lei, Q. Wei, W. Zhu, J. Peng and Y. Cao, Novel cyclometalated platinum (II) complex containing alkyl-trifluorene picolinic acid as emitter for single-layer white PLEDs, Org. Electron. 11, 2010, 1954.

[9] F. Liu, C. Tang, Q.-Q. Chen, F.-F. Shi, H.-B. Wu, L.-H. Xie, B. Peng, W. Wei, Y. Cao and W. Huang, Supramolecular $\pi - \pi$ Stacking Pyrene-Functioned Fluorenes: Toward Efficient Solution-Processable Small Molecule Blue and White Organic Light Emitting Diodes, J. Phys. Chem. C 113, 2009, 4641.

[10] T.-R. Chen, R.-H. Chien, A. Yeh and J.-D. Chen, Synthesis, characterization and electroluminescence of B(III) compounds: BPh2(2-(2-quinolyl)naphtho[b]imidazolato) and BPh2(2-(2-quinolyl)benzimidazolato), J. Organomet. Chem. 691, 2006, 1998.

[11] T.-R. Chen, Luminescence and electroluminescence of bis (2-(benzimidazol-2-yl) quinolinato) zinc. Exciplex formation and energy transfer in mixed film of bis (2-(benzimidazol-2-yl) quinolinato) zinc and N,N'-bis-(1-naphthyl)-N,N'-diphenyl-1,1'-biphenyl-4,4'-diamine, J. Mol. Struct. 737, 2005, 35.

[12] I. Akimoto, S. Tsuzuki, H. Uzawa, M. Hinatsu, Y. Nishide, H. Osuga and H. Sakamoto, Origin of yellow emission in white OLED with single emitting material, Phys. Status Solidi C 8, 2011, 124.

[13] M. Zhu and C. Yang, Blue fluorescent emitters: design tactics and applications in organic light-emitting diodes, Chem. Soc. Rev. 42, 2013, 4963.

[14] R. Kim, S. Lee, K.-H. Kim, Y.-L. Lee, S.-K. Kwon, J.-J. Kim and Y.-H. Kim, Extremely deep blue and highly efficient non-doped organic light emitting diodes unsing an asymmetric anthracene derivative with a xylene unit, Chem. Commun. 49, 2013, 4664.

[15] O. Y. Kim and J. Y. Lee, High efficiency deep blue phosphorescent organic light-emitting diodes using a tetraphenylsilane based phosphine oxide host material, J. Indust. Eng. Chem. 18, 2012, 1029.

[16] S. O. Jeon, S. E. Jang, H. S. Son and J. Y. Lee, External quantum efficiency above 20% in deep blue phosphorescent organic light-emitting diodes, Adv. Mater. 23, 2011, 1436.

[17] S. H. Jeong and J. Y. Lee, Dibenzothiophene derivatives as host materials for high efficiency in deep blue phosphorescent organic light emitting diodes J. Mater. Chem. 21, 2011, 14604.

[18] K. S. Yook and J. Y. Lee, Solution processed multilayer deep blue and white phosphorescent organic light-emitting diodes using an alcohol soluble bipolar host and phosphorescent dopant materials, J. Mater. Chem. 22, 2012, 14546.

[19] S. H. Kim, J. Jang, S. J. Lee and J. Y. Lee, Deep blue phosphorescent organic light-emitting diodes using a Si based wide bandgap host and an Ir dopant with electron withdrawing substituents, Thin Solid Films 517, 2008, 722.

[20] K. S. Yook, S. O. Jeon, C. W. Joo and J. Y. Lee, High efficiency deep blue phosphorescent organic light-emitting diodes, Organic Electronics 10, 2009, 170.

[21] S. O. Jeon, K. S. Yook, C. W. Joo and J. Y. Lee, High-efficiency deep-blue-phosphorescent organic light-emitting diodes using a phosphine oxide and a phosphine sulfide high-triplet-energy host material with bipolar charge-transport properties, Adv. Mater. 22 (2010) 1872.

[22] K. S. Yook, S. O. Jeon, C. W. Joo, J. Y. Lee, M. S. Kim, H. S. Choi, S. J. Lee, C.-W. Han and Y. H. Tak, Highly efficient pure white phosphorescent organic light-emitting diodes using a deep blue phosphorescent emitting material, Organic Electronics 10, 2009, 681.

[23] W. Jiang, Z. Ge, P. Cai, B. Huang, Y. Dai, Y. Sun, J. Qiao, L. Wang, L. Duan and Y. Qiu, Star-shaped dendritic hosts based on carbazole moieties for highly efficient blue phosphorescent OLEDs, J. Mater. Chem. 22, 2012, 12016.

[24] C. Ulbricht, B. Beyer, C. Friebe, A. Winter and U. S. Schubert, Recent Developments in the Application of Phosphorescent Iridium(III) Complex Systems, Adv. Mater. 21, 2009, 4418.

[25] C. Wu, H.-F. Chen, K.-T. Wong and M. E. Thompson, Study of ion-paired iridium complexes (soft salts) and their application in organic light emitting diodes, J. Am. Chem. Soc. 132, 2010, 3133.

[26] F. Dumur, G. Nasr, G. Wantz, C. R. Mayer, E. Dumas, A. Guerlin, F. Miomandre, G. Clavier, D. Bertin and D. Gigmes, Cationic iridium complex for the design of soft salt-based phosphorescent OLEDs and color-tunable light-emitting electrochemical cells, Org. Electron. 12, 2011, 1683.

[27] G. Nasr, A. Guerlin, F. Dumur, L. Beouch, E. Dumas, G. Clavier, F. Miomandre, F. Goubard, D. Gigmes, D. Bertin, G. Wantz and C. R. Mayer, Iridium(III) soft salts from dinuclear cationic and mononuclear anionic complexes for OLED devices, Chem. Commun. 47, 2011, 10698.

[28] F. Dumur, D. Bertin and D. Gigmes, Iridium (III) complexes as promising emitters for solid-state Light-Emitting Electrochemical Cells (LECs), Int. J. Nanotechnol. 9, 2012, 377.

[29] T. Hu, L. He, L. Duan and Y. Qiu, Solid-state light-emitting electrochemical cells based on ionic iridium(III) complexes, J. Mater. Chem. 22, 2012, 4206.

[30] H.-F. Chen, C. Wu, M.-C. Kuo, M. E. Thompson, K.-T. Wong, Anionic iridium complexes for solid state light-emitting electrochemical cells, J. Mater. Chem. 22, 2012, 9556.

[31] A. Kohler, J. S. Wilson and R. H. Friend, Fluorescence and Phosphorescence in Organic Materials, Adv. Mater. 14, 2002, 701.

[32] K. Dedeian, J. Shi, N. Shepherd, E. Forsythe and D.C. Morton, Photophysical and Electrochemical Properties of Heteroleptic Tris-Cyclometalated Iridium(III) Complexes, Inorg. Chem. 44, 2005, 4445.

[33] Y. Chi, P.-T. Chou, Transition-metal phosphors with cyclometalating ligands: fundamentals and applications, Chem. Soc. Rev. 39, 2010, 638.

[34] C.-J. Yang, M. Xu, J.-H. Wang, Y.-Z. Liu and X.-C. Gao, J.-W. Fu, Red to near-infrared electrophosphorescence from a platinum complex coordinated with 8-hydroxyquinoline, Appl. Phys. Lett. 89, 2006, 233506.

[35] L. Murphy and J. A. G. Williams, Luminescent platinum compounds: from molecules to OLEDs, Top. Organomet. Chem. 28, 2010, 75.

[36] B. D'Andrade and S. R. Forrest, Formation of triplet excimers and dimers in amorphous organic thin films and light emitting devices, Chem. Phys. 286, 2003, 321.

[37] C.-H. Yang, S.-W. Li, Y. Chi, Y.-M. Cheng, Y.-S. Yeh, P.-T. Chou, G.-H. Lee, C.-H. Wang and C.-F. Shu, Heteroleptic cyclometalated iridium(III) complexes displaying blue phosphorescence in solution and solid state at room temperature, Inorg. Chem. 44, 2005, 7770.

[38] A. Vogler and H. Kunkely, Luminescent metal complexes: diversity of excited states, Top. Curr. Chem. 213, 2001, 143.

[39] A. B. Tamayo, B. D. Alleyne, P. I. Djurovich, S. Lamansky, I. Tsyba, N. N. Ho, R. Bau and M. E. Thompson, Synthesis and characterization of facial and meridional tris-cyclometalated

iridium(III) complexes, J. Am. Chem. Soc. 125, 2003, 7377.
[40] T. Fei, X. Gu, M. Zhang, C. Wang, M. Hanif, H. Zhang, Y. Ma, Optical and electronic properties of phosphorescent iridium(III) complexes with phenylpyrazole and ancillary ligands, Synth. Met. 159, 2009, 113.
[41] V. Adamovich, J. Brooks, A. Tamayo, A. M. Alexander, P. I. Djurovich, B. W. D'Andrade, C. Adachi, S. R. Forrest and M. E. Thompson, High efficiency single dopant white electrophosphorescent light emitting diodes, New J. Chem. 26, 2002, 1171.
[42] M. Pfeiffer, S. R. Forrest, K. Leo and M. E. Thompson, Electrophosphorescent p–i–n organic light-emitting devices for very-high-efficiency flat-panel displays, Adv. Mater. 14, 2002, 1633.
[43] V. I. Adamovich, S. R. Cordero, P. I. Djurovich, A. Tamayo, M. E. Thompson, B. W. D'Andrade and S. R. Forrest, New charge-carrier blocking materials for high efficiency OLEDs, Org. Electron. 4, 2003, 77.
[44] B. Ma, B. J. Kim, D. A. Poulsen, S. J. Pastine and J. M. J. Fréchet, Multifunctional crosslinkable iridium complexes as hole transporting/electron blocking and emitting materials for solution-processed multilayer organic light-emitting diodes, Adv. Funct. Mater. 19, 2009, 1024.
[45] Y. H. Kim, D. C. Shin, S. H. Kim, C. H. Ko, H. S. Yu, Y. D. Chae and S. K. Kwon, Novel blue emitting material with high color purity, Adv. Mater. 13, 2001, 1690.
[46] S. J. Lee, J. S. Park, K. J. Yoon, Y. I. Kim, S. H. Jin, S. K. Kang, Y. S. Gal, S. W. Kang, J. Y. Lee, J. W. Kang, S. H. Lee, H. D. Park and J. J. Kim, High-efficiency deep-blue light-emitting diodes based on phenylquinoline/carbazole-based compounds, Adv. Funct. Mater. 18, 2008, 3922.
[47] Y. H. Kim, H. C. Jeong, S. H. Kim, K. Yang and S. K. Kwon, Novel blue emitting material with high color purity, Adv. Mater. 13, 2001, 1690.
[48] Z. Deng, S. T. Lee, D. P. Webb, Y. C. Chan and W. A. Gambling, Carrier transport in thin films of organic electroluminescent materials, Synth. Met. 107, 1999, 107.
[49] R. G. Kepler, P. M. Beeson, S. J. Jacobs, R. A. Anderson, M. B. Sinclair, V. S. Valencia and P. A. Cahill, Electron and hole mobility in tris(8-hydroxyquinolinolato-N1,O8) aluminum, Appl. Phys. Lett. 66, 1995, 3618.
[50] C. Weichsel, S. Reineke, M. Furno, B. Lüssem and K. Leo, Organic light-emitting diodes for lighting: High color quality by controlling energy transfer processes in host-guest-systems, J. Appl. Phys. 111, 2012, 033102.
[51] L. Duan, L. Hou, T.-W. Lee, J. Qiao, D. Zhang, G. Dong, L. Wang and Y. Qiu, Solution processable small molecules for organic light-emitting diodes, J. Mater. Chem. 20, 2010, 6392.

Received July 10, 2013; accepted October 26, 2013.