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Exceptional Hybrid White Organic Light-Emitting Diodes with paper- thin Blue & Orange Emissive Layers, Achieving High Efficiency

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Abstract:

In the research paper are Using the delta-doping technique, two brand-new, efficient hybrid white organic light-emitting diodes were made. A inadequate efficiency retract, the circuit with a single paper-thin emissive layer has brightness of a 46923 cd/m^2. A second apparatus with two paper-thin emissive layers accomplishes inadequate controlling voltages, good efficiency (8.9lm/W), with a raised color rendering measurement (75), therefore simplifying the component's architectures even more. Furthermore, it is discovered that these two devices display a rather consistent color in addition to a pretty pure white emission. These enhanced characteristics show that using delta-doping technological devices offers a fresh approach producing high- the implementation electronics.

Introduction:

White organic light emitting diode (WOLEDs) is increasingly relied panel sectors with are currently being researched for potential lighting potential in the years to come. This is because they provide significant benefits, including high efficiency, small size and cost. The provided input is an inventory that consists of the items 1 and 3. Researchers globally have recently suggested many efficient techniques for producing white the brightness, similar colour down transformation the media sources, exciplex / excimer structures, single molecule architectures, p–i–n junctions, tandems, microcavities, as well as solution-processed polymeric materials. The effectiveness of WOLEDs has been progressively enhanced through these improvements.

Commonly, the doping procedure is frequently used for obtaining a white hue, which became widely utilized in small-molecule along with polymer equipment to generate white illumination. This method has resulted in the creation of multiple very efficient as well as radiant WOLEDs.

The range of numbers is from [11-13] the methodology of incorporating red green and blue dopants inside their corresponding host surfaces lacks efficiency in Be in charge of the deposition allowance of materials & uniformity of the concentration of dopant across the entire manufacturing procedure. Furthermore, both multi-host-surfaces and single-host-surface WOLEDs need a multitude of utilitarian materials and complex manufacturing techniques, leading to elevated prices in comparison to its monochromatic counterpart.

Introduction

In addition to the use of dye-doped host materials for the development of efficient white organic light-emitting diodes (WOLEDs), other approaches such as delta-doping have been suggested. This involves the introduction of a single undoped dye layer (or many very thin undoped dye layers) into the emissive layer (EML). [14 to 20]. WOLEDs using the delta-doping process have gained significant attention in recent times because to their uncomplicated architectures and exceptional repeatability. These characteristics make them highly suitable for cost-effective applications and advantageous for industrial implementation. Tsuji et al. reported the first undoped WOLED, which subsequently garnered significant interest. As an example, Ma et al. created luminous white organic light-emitting diodes (WOLEDs) by including an extremely thin layer (0.05 nm) of 3-(dicyanomethylene)-5,5-dimethyl-1-(4-dimethylamino-styryl) cyclohexene between bipolar emitters.[15] Yang successfully fabricated multilayer fluorescent WOLEDs by combining a blue fluorescent dye with a dual sub-monolayer (0.1 nm).16) Zhao et al. created phosphorescent WOLEDs using a very thin undoped orange EML (as thin as 0.1 nm). This experiment showed that it is feasible to manufacture WOLEDs with almost perfect internal quantum efficiency by the delta-doping technique. The user's text is a numerical reference to a source or citation. Subsequently, Zhao and colleagues used paper-thin phosphorescent dyes with a size of 0.1 nm to exhibit a range of complementary phosphorescent WOLEDs, which exhibited excellent white emission and great efficiency. [19]. Based on these findings, it may be inferred that delta doping technology is a very promising method for creating simple and effective WOLEDs. Nevertheless, the brightness of fluorescent WOLEDs using delta-doping method is still insufficient, with the efficiency never surpassing 6.7 lm/W.[15 to 17] Conversely, the colour of phosphorescent WOLEDs implemented by this technique often exhibits instability. [18 to 20] Furthermore, due to the absence of a reliable blue phosphorescent emitter with a long lifespan, the use of this method in phosphorescent WOLEDs results in a very low lifespan, rendering it unsuitable for commercialization. Considering these facts, there is a pressing need for efficient, luminous, color-stable, and uncomplicated devices to meet the practical requirements of WOLEDs. This suggests that there is significant potential to improve the performance of WOLEDs by the use of delta doping technology. An effective and favorable technique to resolve the conflicts mentioned above is the use of hybrid white organic light-emitting diodes (HWOLEDs). These diodes combine stable blue fluorescent emitters with phosphorescent green-red/orange emitters. [12 to 13]. Nevertheless, despite the many benefits of HWOLEDs, including their high efficiency and extended lifespan, there have been no reports of HWOLEDs with paper-thin emissive layers measuring less than 1 nm.

Working and Operation

This article presents the development of a new kind of HWOLED that includes an extremely thin blue EML. By optimizing the process, we achieved a maximum forward-viewing power efficiency (PE) of 7.3 lm/W and a luminance of 46923 cd/m2. In addition, the decrease in efficiency is minimal and the colour of the gadget is not much affected by the voltage applied. Furthermore, a comprehensive examination of spacers has been shown, illustrating the indispensability of the N,N0-bis(naphthalene-1-yl)-N,N0-diphenylbenzidine (NPB) spacer in achieving optimal performance in this device. Considering these considerations, we have suggested a new HWOLED design that consists of two very thin EMLs, each measuring less than 1 nanometer. Notably, the device has very low driving voltages, namely 2.7V for 1 cd/m2, 3.4V for 100 cd/m2, and 4.1V for 1000 cd/m2. It also has a power efficiency (PE) of 8.9 lm/W and a colour rendering index (CRI) of 75. For comparative purposes, we manufactured HWOLEDs utilizing a comprehensive doping technique, which resulted in clearly evident outcomes.

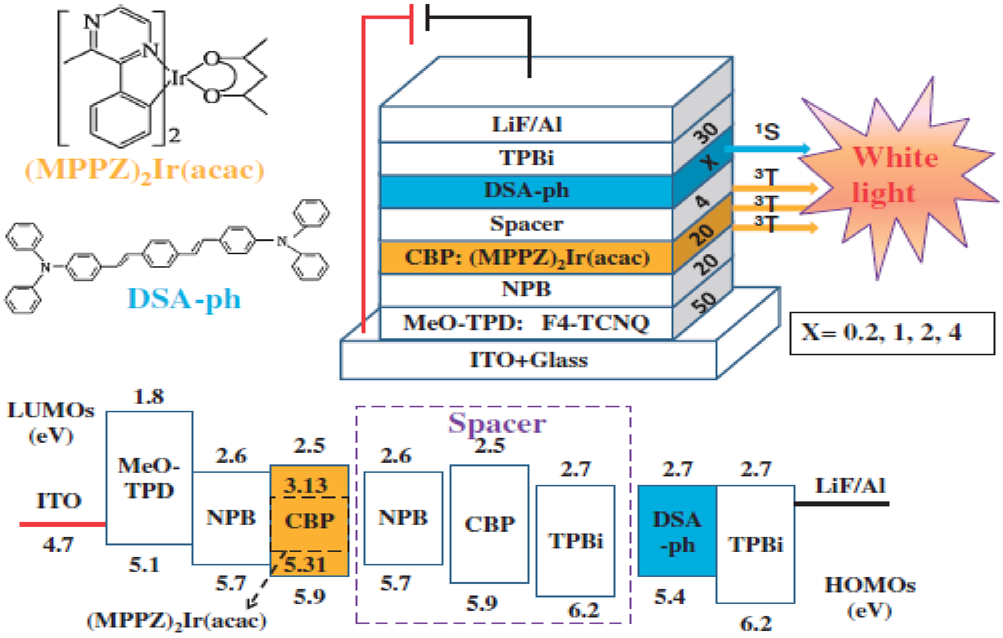

Figure 1 illustrates the chemical structure of emissive components and a schematic of produced HWOLEDs. The idea for an energy-level schematic for HWOLEDs uses data from research.[22,25–28]

The purpose is to demonstrate the flexibility of delta-doping devices by examining their reliance on the host material.

The configuration of devices W11-W14, as shown in Figure 1, is ITO/MeO-TPD:F4-TCNQ (50 nm, 4%)/NPB (20 nm)/CBP:(MPPZ)2Ir(acac) (20 millimetres, 8%)/NPB (4 nm)/DSA-ph (x nm)/TPBi (30 nm)/LiF (1 nm)/Al (200 nm). In this setting, ITO refers to indium tin oxide, F4-TCNQ is tetrafluoro-tetracyanoqino dimethane, which is doped into N,N,N0,N0-tetrakis(4-methoxyphenyl)-benzidine (MeO-TPD), and iridium(III) diazine complexes (MPPZ)2Ir(acac) act as an orange guest. [22] The compound doped into a 4,4-N,N-dicarbazolebiphenyl (CBP) is DSA-ph, which stands for p-bis(p-N,N-di-phenyl-aminostyryl) benzene. TPBi refers to 2,20,200-(1,3,5-benzinetriyl)-tris(1-phenyl-1-H-benzimidazole). Lastly, the cathode was formed by depositing LiF/Al using a shadow mask. Devices W11, W12, W13, and W14 correspond to DSA-ph measurements of 0.2, 1, 2, and 4 nm, correspondingly. The equipment were fabricated and measured using standard procedures, as documented in another source [23].

The figure shown in Figure 2 displays the CE as well as PE values for devices with varying thicknesses of DSA-ph, as a function of current density. The superior efficiency of device W11 are clearly evident when compared to competing devices. When the thickness of DSA-ph grows from 0.2 to 4 nm, both the charge efficiency (CE) and power efficiency (PE) of the devices decline significantly. This suggests that a very thick blue emissive layer (EML) is not appropriate for this device design. The loss in instrument efficiency may be ascribed to the intensification of concentration quenching, which becomes more severe when the undoped EML depth increases [17,18]. The highest current efficiency (CE) for device W11 is 8.7 cd/A, while the maximum power efficiency (PE) is 7.3 lm/W. Surprisingly, it has been shown that W11 has a significant decrease in efficiency when it operates at higher levels. In this case, a maximum current efficiency (CE) of 8.7 cd/A is achieved at a brightness of 480 cd/m2 (5.5 mA/cm2). This CE value stays constant even at a high luminance of 1700 cd/m2 (19.1 mA/cm2). Furthermore, with a luminance of 10000 cd/m2, the CE only slightly decreases to 7.8 cd/A. Our innovative device efficiently addresses the efficacy roll-off issue, which is often seen in conventional phosphorescent WOLEDs [10] and some reported HWOLEDs [12].

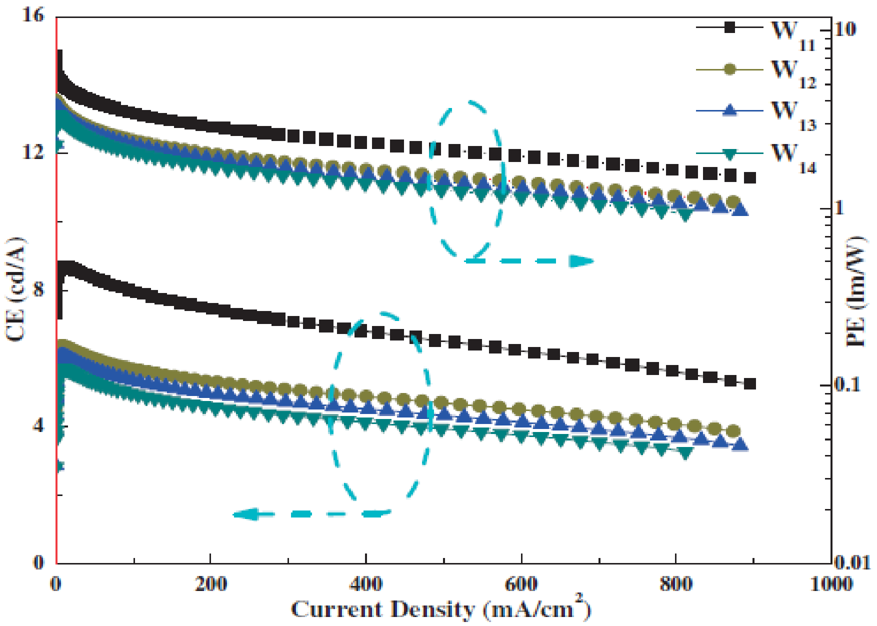

Figure 2 demonstrates the HWOLEDs' CE as well as PE in relation to electric current intensity.

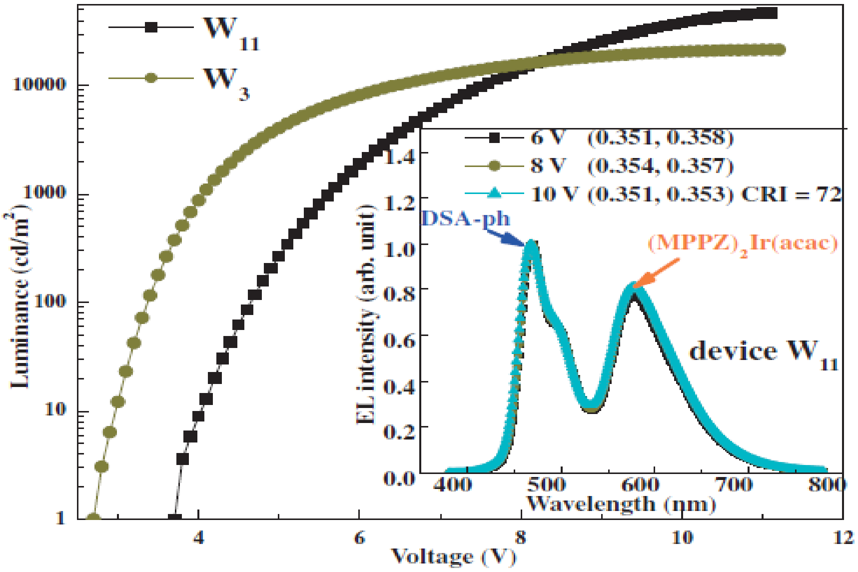

Figure 3 illustrates Instruments W11 as well as W3's luminance-voltage correlations. EL spectrum of sensor W11 at different voltages is illustrated.

Figure 3 depicts the relationship between brightness and voltage for W11. The turn-on voltage for this piece of equipment, which is defined as the voltage at which it reaches an illuminance of 1 cd/m2, is 3.7 V. The greatest recorded brightness in WOLEDs with a delta-doping EML is 46923 cd/m2, achieved at 11.1V. In addition, the spectrum consistency is examined when the applied energies are altered. It is found that there is no noticeable change in colour in W11 when the driving voltage varies, as shown in Figure 3 (inset). The Commission Internationale de L'Eclairage (CIE) coordinates in W11 are (0.351, 0.358) at 6V, (0.354, 0.357) at 8V, and (0.351, 0.353) at 10V, which closely approximate the white equivalent-energy point (0.333, 0.333). The CIE values of W11 exhibit a total fluctuation of ð0:003; 0:005Þ, indicating remarkable colour equilibrium.

The voltage attained was 11.1V, the sense that as far as we know, is the greatest value achieved in WOLEDs with a delta-doping EML. Furthermore, the study also examines the spectrum stability when the applied voltages are altered. It is noticed that there is no noticeable change in colour in W11 when the driving voltage varies, as shown in Fig. 3 (inset). The Commission Internationale de L'Eclairage (CIE) coordinates in W11 are (0.351, 0.358) at 6V, (0.354, 0.357) at 8V, and (0.351, 0.353) at 10V, which closely approximate the white equivalent-energy point (0.333, 0.333). The CIE coordinates have a total fluctuation of ð0:003; 0:005Þ, indicating that W11 has exceptional colour consistency.

An essential aspect of creating HWOLEDs is the use of a suitable spacer positioned both fluorescent as well as phosphorescent emitters. This distinguishes HWOLEDs from fluorescent and phosphorescent WOLEDs. [12] In order to elucidate the importance of the NPB spacer in the innovative device, we used TPBi (device W21) and CBP (device W22) as alternative spacers. Additionally, a HWOLED without any spacing was created (device W23) for comparative purposes. The spectra of the aforementioned devices at different voltages are shown in Figure 4. It is worth noting that there is only a little amount of blue emission produced in W21 and W23. For W22, it is seen that when the voltage rises from 6 to 10V, the emissions are situated inside the white zone. However, it not only has a yellowish white colour, which is significantly different from the desired coordinates of ð0:333; 0:333Þ, but also has a low Colour Rendering Index (CRI) of 55. In addition, the overall fluctuation in the range (0.013, 0.007) is much more than that of W11. The causes of these events may be elucidated as follows. Due to the Dexter energy transfer taking place within a range of 1-2 nm [24], and the Fo¨rster radius being 3 nm [12], the lack of an effective spacer does not hinder the energy transfer between the fluorescent DSA-ph emitter and phosphorescent (MPPZ)2Ir(acac) emitter. Consequently, this results in the absence of blue emission in W23. In W21, the triplet energy of the 4 nm TPBi spacer is measured to be 2.74 eV,25), indicating that it effectively inhibits the transmission of energy between the emitters. TPBi is classified as an electron-type material [25], and there is a significant barrier energy of 0.3 eV between CBP and TPBi. This barrier effectively prevents the movement of holes from CBP to TPBi.

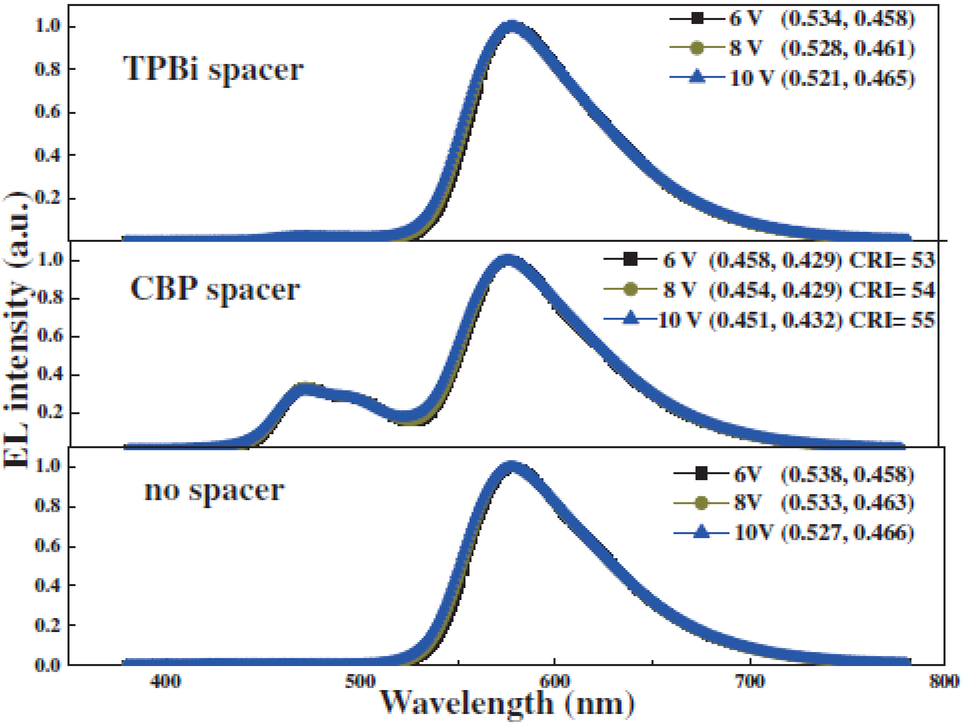

Figure 4: EL the spectrum in equipment with various spacing.

Therefore, only a limited number of holes are able to reach the blue zone and undergo recombination with electrons, leading to the absence of white light in W21. In the case of W22, the presence of a 4 nm CBP spacer effectively inhibits energy transfer due to the high triplet energy (2.56 eV) of CBP, which is a material that exhibits both electron and hole conduction properties. Consequently, we propose that a smaller number of holes are able to reach the blue layer, while the majority of holes are transported exclusively to the orange EML. Here, they recombine with electrons injected from the cathode, resulting in the emission of orange light. Therefore, the spectra that are produced are mostly influenced by the (MPPZ)2Ir(acac) emission, resulting in a yellowish white light. In W11, the use of a 4 nm NPB spacer serves two purposes. Firstly, it inhibits Fo¨rster energy transfer from the blue fluorescent emitter to the orange phosphorescent emitter. Secondly, it removes the nonradiative Dexter potential transfer across both layers, which is caused by the high triplet energy (2.3 eV).The number is 28. Moreover, the NPB possesses the characteristic of facilitating the movement of holes while hindering the movement of electrons. This feature effectively maintains a balance between the injection and transportation of electrons and holes in areas emitting orange and blue light. As a result, it reduces the decline in efficiency and ensures a consistent white emission.

Based upon our successful outcomes, researchers proceeded to create a HWOLED with two very thin Emissive Layer (EML) [12] components (device W3). Notably, the orange EML is likewise an paper-thin layer. The optimised configuration consists of the following layers: ITO/MeO-TPD:F4-TCNQ (50 nm, 4%)/NPB (20 nm)/ (MPPZ)2Ir(acac) (0.5 nm)/NPB (4 nm)/DSA-ph (0.2

nm)/ TPBi (30 nm)/LiF (1 nm)/Al (200 nm). Figure 5 displays the CE and PE of W3 as an indication of the electrical density. The enlargement provides a visual representation of the spectra of W3 at different voltages. Remarkably, W3 has a maximum forward-viewing CE of 7.6 cd/A and a PE of 8.9 lm/W, surpassing W11 by 22% in both aspects. Our gadget has a maximum total luminous efficacy (PE) of 15.1 lm/W, which is similar to the efficiency of incandescent light bulbs (12-17 lm/W). Brightness sources are often evaluated based on their total output power. Achieving a luminance of 1000 cd/m2 (16.0 mA/cm2) allows for a luminous efficacy of 6.5 cd/A and a power efficacy of 5.0 lm/W. In addition, over a wide variety of brightness levels ranging from 13 cd/m2 (3 V) to 4052 cd/m2 (5 V), the colour shift is just ð0:001; 0:004Þ. This indicates that the new device maintains a rather consistent colour, demonstrating its stability. Given that most previously reported high-efficiency white organic light-emitting diodes (HWOLEDs) tend to have a yellowish white colour, with only a small number achieving a pure white colour, our device successfully addresses this limitation. Specifically,

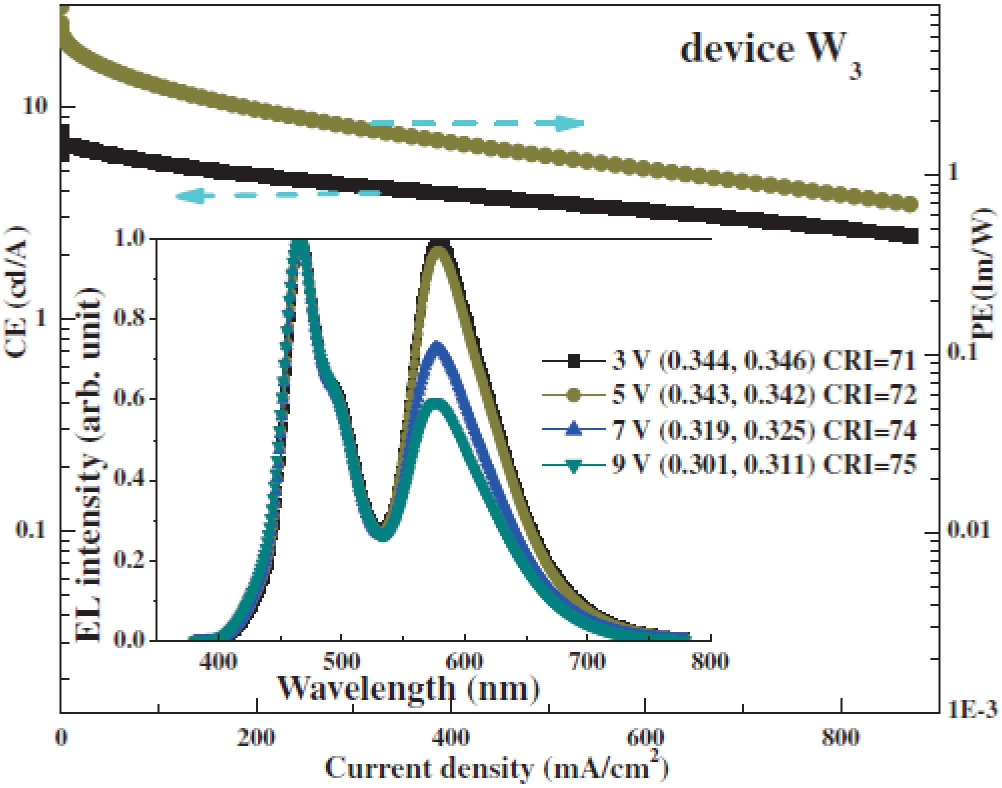

Figure 5 illustrates W3's CE as well as PE in relation to current density. EL spectrum of W3 at various voltages is highlighted.

Our device, denoted as W3, consistently displays very pure colours that closely resemble (0.333, 0.333) across all driving voltages, as illustrated in Figure 5 (inset). Furthermore, a remarkable Colour Rendering Index (CRI) of 75, the highest ever recorded in two-color White Organic Light Emitting Diodes (WOLEDs) with paper-thin Emissive Layer (EML) thicknesses of less than 1 nanometer, is attained at a voltage of 9 volts. To our understanding, the CRI is the highest among two-color HWOLEDs based on Ir-complexes that have been reported in the literature so far. Significantly, as seen in Figure 3, the activation voltage of W3 is very low at 2.7 V. This value is the most minimal recorded in spacer-based HWOLEDs without p-i-n architectures, to the best of our understanding. The voltage applied is 3.4 V at a brightness of 100 cd/m2, which is important for the display. At a brightness of 1000 cd/m2, the voltage applied is 4.1V, resulting in a high luminance of 21490 cd/m2 at 11.2V. Given the current difficulties in achieving low driving voltages for practical application in WOLEDs [11] (e.g., less than 3V for onset and less than 4V at 100 cd/m2 for compact projection), it is evident that our technology may successfully address this obstacle.

FABRICATION OF OLED DEVICES

For the purpose of to showcase the capabilities of devices through delta doping technique, we constructed 3 HWOLEDs containing fully doped EMLs. The blue the host material that was utilised in these devices is either NPB or MADN, since these hosts have been shown to be best suited for DSA-ph guest.The device architectures are described thoroughly below:

W41: MPPZ)2Ir(acac) (20 nm, 8%)/NPB (4 nm)/ITO/MeO-TPD:F4-TCNQ (50 nm, 4%)/NPB (20 nm)/ TPBi (30 nm):DSA-ph (20 nm, 7%)/LiF/Al

W42: MPPZ)2Ir(acac) (20 nm, 8%)/NPB (4 nm)/ITO/MeO-TPD:F4-TCNQ (50 nm, 4%)/NPB (20 nm)/ TPBi (30 nm) / MADN:DSA-ph (20 nm, 7%)/LiF/Al

W43: MPPZ)2Ir(acac) (20 nm, 8%)/NPB (4 nm)/ITO/MeO-TPD:F4-TCNQ (50 nm, 4%)/NPB (20 nm)TPBi (30 nm) /MADN:DSA-ph (20 nm, 7%)/LiF/Al

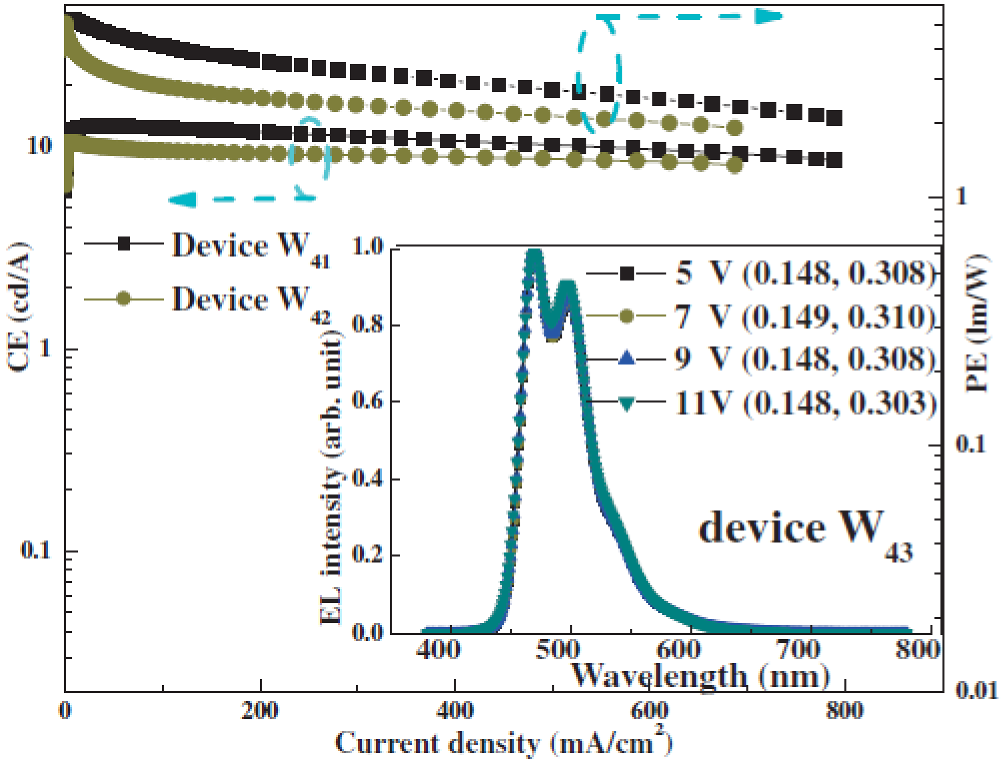

Figure 6: The current density-dependent CE and PE of equipment W41 as well as W43.EL spectra for the W43 transistor at different voltages are illustrated.

Table I represents a concise overview of the functionality of the manufactured HWOLED modules.

Device	**$V_{on=1000}$ (V)**	**$CE_{Max=1000}$ (cd/A)**	**$PE_{Max=1000}$ (lm/W)**
W11	3.7/5.6	8.7/8.7	7.3/4.9
W3	2.7/4.1	7.6/6.5	8.9/5.0
W41	5.0/8.4	10.5/10.4	5.1/3.9
W42	4.5/7.2	12.7/12.1	5.3/5.2

Both Figure 6 as well as Table I provide a concise overview of both the CE and PE attributes of W41 and W42. The highest current efficiencies (CEs) for W41 as well as W42 are 12.7 and 10.5 cd/A, respectively. It is readily apparent that in the case of all-doped EML equipment, when MADN is utilised as the host material, a greater charge efficiency (CE) is achieved. However, when NPB is used as the host material, the excitons are not successfully used, suggesting that the nonradiative decay of excitons or exciton quenching is more significant in NPB compared to MADN.19th In addition, the device with MADN and NPB as the host has power efficiencies (PEs) of 5.3 and 5.1 lm/W, correspondingly. These values are 40% lower when compared to the PE of W11 (7.3 lm/W) and 70% lower than the PE of W3 (8.9 lm/W). The larger PEs of W11 and W3 may be attributed to the decreased thickness of EMLs compared to W41 and W42. However, W43 does not produce any orange emission, as seen in Figure 7 (inset). Based on these findings, it can be inferred that utilising unsuitable hosts may significantly degrade device performances and achieving efficient emission of multiple dyes using a single host is challenging. In contrast, undoped EML structures not only circumvent the issue of selecting a host material but also exhibit a streamlined manufacturing process, therefore significantly reducing the expenses associated with applications in commerce.

Conclusion / Results

Researchers invented two new outstanding performance. HWOLEDs using the delta-doping technique. The instrument achieves an paper-thin blue EML, with a luminous efficacy of 7.3 lm/W, a brightness of 46923 cd/m2, and little efficiency roll-off. Upon examining the importance of the spacer, this is determined because NPB is crucial for achieving maximum efficiency. Additionally, in order to streamline instrument designs even more, another High-Workfunction Organic Light-Emitting Diode (HWOLED) has been suggested, which consists of two very thin Emissive Layer Materials (EMLs). The optimised device demonstrates remarkable performance with low driving voltages, a high Colour Rendering Index (CRI) of 75, and a high efficiency of 8.9 lumens per watt (lm/W). Furthermore, it has been discovered that each of these devices not only demonstrate a very pure white emission, but also maintain a consistent and constant colour. Delta-doping devices provide more versatility compared to all-doping devices that are reliant on a certain host. Due to the ongoing interest in designing simpler structures that facilitate low-cost mass manufacturing of OLEDs, our innovative device architectures are well-suited for this reason. Researchers anticipate that this strategy will provide significant benefits in future actual implementation due to the judicious selection of materials.

References

[1] H. Sasabe and J. Kido: J. Mater. Chem. C 1 (2013) 1699.
[2] G. Lecamp: SID Symp. Dig. Tech. Pap. 44 (2013) 597.
[3] X.-B. Shi, C.-H. Gao, D.-Y. Zhou, M. Qian, Z.-K. Wang, and L.-S. Liao: Appl. Phys. Express 5 (2012) 102102.
[4] S. Chen and H.-S. Kwok: Org. Electron. 12 (2011) 677.
[5] Q.-X. Tong, S.-L. Lai, M.-Y. Chan, J.-X. Tang, H.-L. Kwong, C.-S. Lee, and S.-T. Lee: Appl. Phys. Lett. 91 (2007) 023503.
[6] G. L. Tu, C. Y. Mei, Q. G. Zhou, Y. X. Cheng, Y. H. Geng, L. X. Wang, D. G. Ma, X. B. Jing, and F. S. Wang: Adv. Funct. Mater. 16 (2006) 101.
[7] G. Schwartz, S. Reineke, K. Walzer, and K. Leo: Appl. Phys. Lett. 92 (2008) 053311.
[8] L. Duan, T. Tsuboi, Y. Qiu, Y. Li, and G. Zhang: Opt. Express 20 (2012) 14564.
[9] H. Zhang, H. You, J. Shi, W. Wang, S. Guo, M. Liu, and D. Ma: Synth. Met. 156 (2006) 954.
[10] B. Zhang, G. Tan, C.-S. Lam, B. Yao, C.-L. Ho, L. Liu, Z. Xie, W.-Y. Wong, J. Ding, and L. Wang: Adv. Mater. 24 (2012) 1873.
[11] Z. Zhang, P. Yan, S. Yue, Y. Chen, Q. Wu, D. Qu, R. Guo, P. Wang, Y. Zhao, and S. Liu: Org. Electron. 14 (2013) 2172.
[12] Y. Sun, N. C. Giebink, H. Kanno, B. Ma, M. E. Thompson, and S. R. Forrest: Nature 440 (2006) 908.
[13] G. Schwartz, M. Pfeiffer, S. Reineke, K. Walzer, and K. Leo: Adv. Funct. Mater. 19 (2007) 3672.
[14] T. Tsuji, S. Naka, H. Okada, and H. Onnagawa: Appl. Phys. Lett. 81 (2002) 3329.
[15] Z. Ma, J. Yu, L. Li, and Y. Jiang: Displays 33 (2012) 42.
[16] H. Yang: J. Lumin. 142 (2013) 231.
[17] Q. Xue, S. Zhang, G. Xie, Z. Zhang, L. Zhao, Y. Luo, P. Chen, Y. Zhao, and S. Liu: Solid-State Electron. 57 (2011) 35.
[18] Y. Zhao, J. Chen, and D. Ma: Appl. Phys. Lett. 99 (2011) 163303.
[19] Y. Zhao, J. Chen, and D. Ma: ACS Appl. Mater. Interfaces 5 (2013) 965.
[20] J. Zhao, J. Yu, X. Hu, M. Hou, and Y. Jiang: Thin Solid Films 520 (2012) 4003.
[21] H. Sasabe, K. Minamoto, Y.-J. Pu, M. Hirasawa, and J. Kido: Org. Electron. 13 (2012) 2615.
[22] G. Ge, J. He, H. Guo, F. Wang, and D. Zou: J. Organomet. Chem. 694 (2009) 3050.
[23] B.-Q. Liu, H. Tao, Y.-J. Su, D.-Y. Gao, L.-F. Lan, J.-H. Zou, and J.-B. Peng: Chin. Phys. B 22 (2013) 077303.

[24] P. Chen, W. Xie, J. Li, T. Guan, Y. Duan, Y. Zhao, S. Liu, C. Ma, L. Zhang, and B. Li: Appl. Phys. Lett. 91 (2007) 023505.

[25] C.-H. Gao, D.-Y. Zhou, W. Gu, X.-B. Shi, Z.-K. Wang, and L.-S. Liao: Org. Electron. 14 (2013) 1177.

[26] K. Goushi, R. Kwong, J. J. Brown, H. Sasabe, and C. Adachi: J. Appl. Phys. 95 (2004) 7798.

[27] B. D. Chin, M. C. Suh, M.-H. Kim, S. T. Lee, H. D. Kim, and H. K. Chung:Appl. Phys. Lett. 86 (2005) 133505.

[28] Q. Wang, J. Ding, Y. Cheng, L. Wang, and D. Ma: J. Phys. D 42 (2009) 065106.

[29] H. M. Zhang, W. C. H. Choy, and K. Li: IEEE Trans. Electron Devices 57 (2010) 125.