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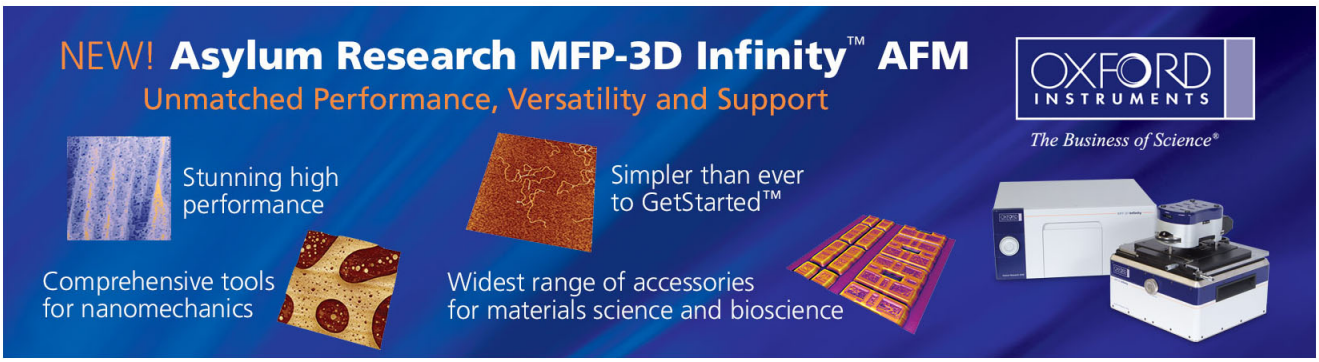

Highly efficient and stable sky blue organic light-emitting devices

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A highly efficient and stable sky blue organic light-emitting device doped with a sky blue dopant BUBD-1 has been fabricated, achieving an electroluminescence efficiency of 13.2 cd/A and 6.1 lm/W at 20 mA/cm^2 and 6.7 V, with Commission Internationale del'Eclairage coordinates of (0.16, 0.30) and a half-decay lifetime of 1815 h at an initial brightness of 2640 cd/m^2. This performance is one of the best blue devices ever reported without using hole blocking layer or any *p or n* dopant in hole or electron transport layer. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2356903]

To date, white light organic light-emitting devices (OLEDs) have drawn intensive studies due to their potential applications in full color display fabrication with color filters,[1] in backlight for liquid crystal display, as well as in solid-state lightings.[2] One of the best known methods to achieve white light OLEDs is the two-color system of sky blue and yellow or orange emission, which has been widely reported.[3–5] In this system, it has been shown that white light OLEDs can be improved significantly by the sky blue emitters in terms of high efficiency, color tuning, and operational stability.[6,7] For doped sky blue emitter using guest/host strategy, up to now, there have been a number of blue host materials that were reported in the literature, namely, anthracene derivatives,[8,9] di(styryl)arylene (DSA),[10] pyrene,[11] fluorene,[12] and silole derivatives.[13] However, information of the optimized and energetically matching sky blue dopant materials remains sketchy and often guarded by various patents or trade secrets. For example, according to published literature, there were only two reports where considerable details have been disclosed with respect to the structures of sky blue electroluminescent materials and devices. One is the robust sky blue dopant *p*-bis(*p*-*N*,*N*-diphenylaminostyryl)benzene (DSA-Ph) which was reported by National Chiao Tung University OLED group, achieving an electroluminescence (EL) efficiency of 9.7 cd/A and 5.5 lm/W at 20 mA/cm^2 with a Commission Internationale del'Eclairage (CIE$_{x,y}$) coordinates of (0.16, 0.32) and a half-decay lifetime ($t_{1/2}$) of 2400 h (L_0 =1940cd/m^2).[6] The other paper was reported by the Canon group who used the Idemitsu sky blue dopant IDE-102 in their proprietary blue host 1,3,5-tri(1-pyrenyl)benzene and achieved an efficiency of 6.0 lm/w with a CIE$_{x,y}$ of (0.19, 0.33) at 5 V with 820 cd/m^2 and a $t_{1/2}$ of 820 h (L_0 =820 cd/m^2).[7]

Here, we report the development of a sky blue fluorescent dopant material BUBD-1, which was doped in a morphologically stable high-band-gap host material, 2-methyl-9,10-di(2-naphthyl)anthracene (MADN); excellent performances of this device have been obtained, achieving an EL efficiency of 13.2 cd/A and 6.1 lm/W at 20 mA/cm^2 and 6.7 V, with CIE$_{x,y}$ of (0.16, 0.30) and a $t_{1/2}$ of 1815 h at L_0=2640 cd/m^2.

The structures of BUBD-1 and MADN along with the sky blue device studied are shown in Fig. 1, where 4,4′,4″-tris[*N*-(1-naphthyl)-*N*-phenylamino]triphenylamine, *N*,*N*′-bis-(1-naphthyl)-*N*,*N*′-diphenyl,1,1′-biphenyl-4,4′-diamine (NPB), and tris(8-quinolinolato)aluminium were used as hole injection, hole transport and electron transport, materials, respectively. Prior to depositing organic materials, the indium tin oxide (ITO) was cleaned with a routine cleaning procedure.[14] The device was fabricated in a standard vacuum coater under the base vacuum of about 10^{-6} Torr. The MADN:BUBD-1 emissive layer was codeposited simultaneously with a series of controlled ratios. The characteristics of current-density–voltage–luminance (*J-V-L*) of the devices have been measured by PR650 spectrophotometer with a dc source controlled by a connected computer.

The energy gap of BUBD-1 with a lowest unoccupied molecular orbital/highest occupied molecular orbital level of 2.6/5.1 eV as shown in Fig. 1 is well confined in MADN. Similar to DSA-Ph-doped device,[6] BUBD-1 doped in MADN also shows the advantage of the absence of the *current-induced quenching* and an effective pathway for both electrons and holes transported into the emitter for efficient recombination, as shown in Fig. 2. We also find that the LUMO and HOMO of BUBD-1 are close to the energy levels of cathode Al and anode ITO, enough to cause carrier trapping,[15] namely, holes and electrons are easier to transport to BUBD-1 than MADN even at low current density. Moreover, from the energy diagram, it is clear that NPB can act as a substantial electron-blocking layer, which also improves

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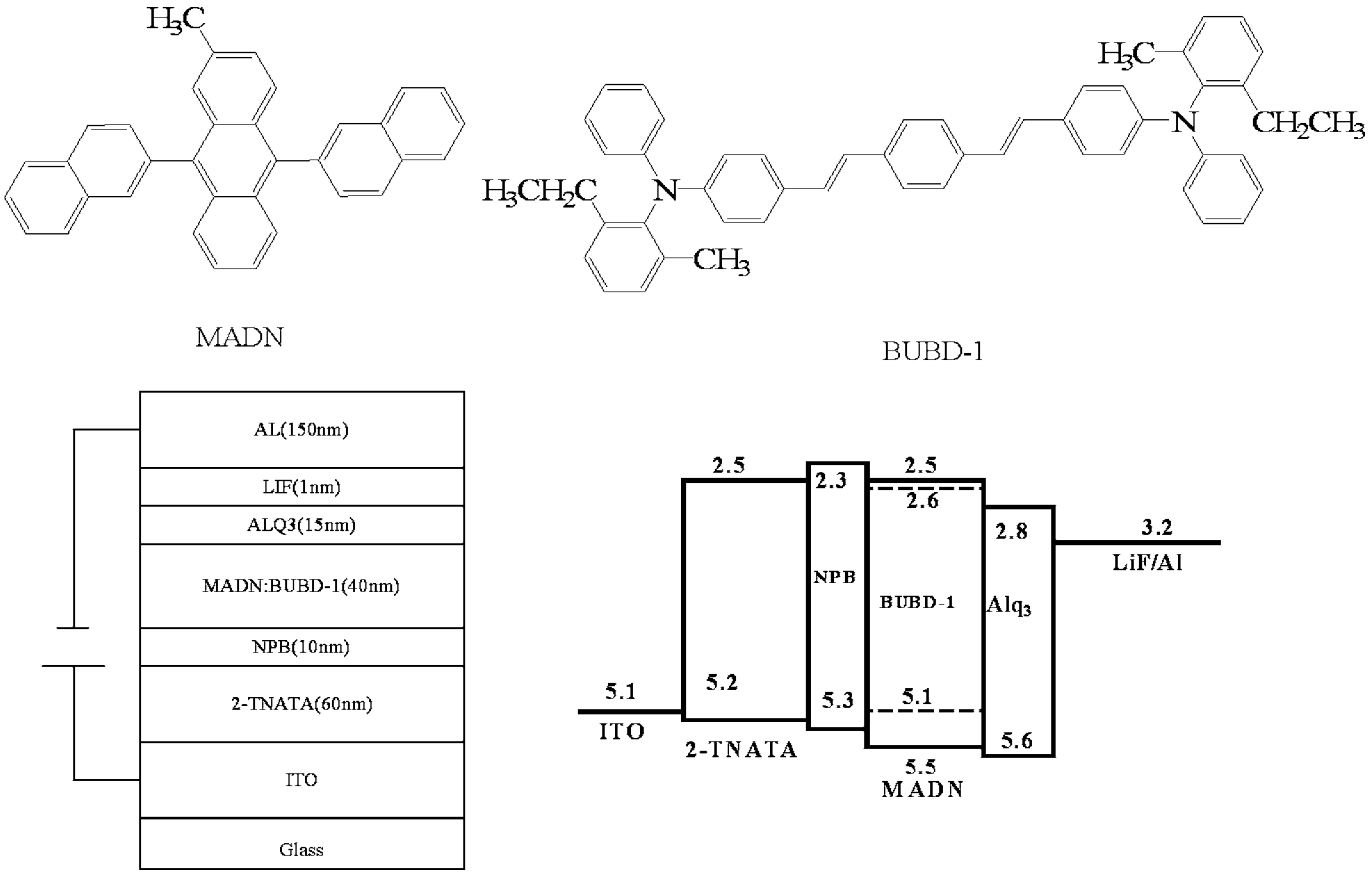

FIG. 1. Configuration, molecular structures of MADN and BUBD-1, and energy diagram of blue-doped device.

the efficiency of recombination by confining the electron-hole pairs in the emission layer. At high current density, both excitation mechanism of charge trapping and Förster energy transfer from host to dopant are evident. It is noteworthy that when the dopant ratio increased to 8%, the efficiency of the device dropped quickly comparing with that of 3% doped device. This phenomenon suggests considerable self-quenching of the dopant upon excitation when excess molecules of BUBD-1 have been codeposited.

Based on the detailed EL performances of the devices measured at 20 mA/cm^2 as shown in Table I, we find that the optimal BUBD-1 concentration in MADN is about 3%. The efficiency is nearly 1.4 times higher than that of DSA-Ph/MADN system of 9.7 cd/A reported previously.[6] This result implies that the enhancement is likely to have arisen from the enhanced spectral overlap of the absorption of BUBD-1 than that of DSA-Ph with the photoluminescence (PL) of MADN, which improves the efficiency of Förster energy transfer significantly. The efficiency of 3% doped device rises sharply at low current densities to a maximum of about 13.2 cd/A at 20 mA/cm^2 and then falls off slowly at higher current densities. Up to about 100 mA/cm^2, the efficiency is still maintained near 13 cd/A. There is practically no EL color shift with varying drive currents. The CIE$_{x,y}$ color coordinates only shift from [0.164; 0.311] at 1 mA/cm^2 to [0.162; 0.307] at 100 mA/cm^2 with $\Delta x,y = \pm[0.002, 0.004]$. The undoped device also showed similar behavior except that the overall efficiency is somewhat lower.

The EL spectra of the undoped device as depicted in Fig. 3 clearly indicate a pure blue emission of MADN with CIE$_{x,y}$ (0.15, 0.10) and a dominant peak at 440 nm while both doped devices are shown to be redshifted and located at 464

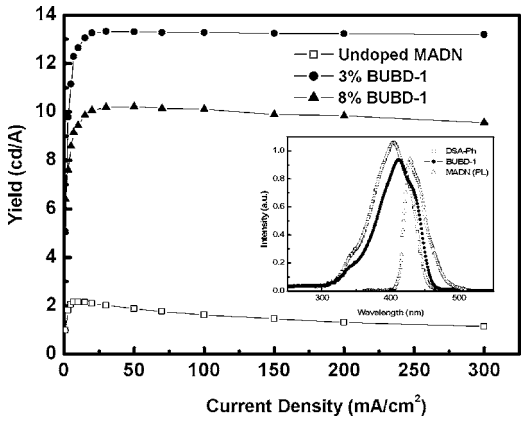

FIG. 2. Dependence of the EL efficiency on the drive current density for undoped and BUBD-1 doped devices and solid PL of MADN overlaid with the absorptions of DSA-Ph and BUBD-1.

TABLE I. EL performances of undoped and BUBD-1 doped devices driven at 20 mA/cm^2.

BUBD-1 doping (%)	Voltage (V)	Luminescence yield (cd/A)	Efficiency (lm/W)	EQE (%)	CIE	
					x	*y*
0	7.8	2.1	0.8	2.0	0.15	0.10
3	6.7	13.2	6.1	6.5	0.16	0.30
8	7.4	10.1	4.3	4.6	0.17	0.33

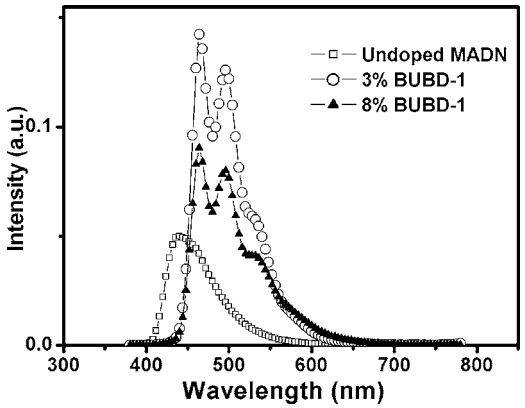

FIG. 3. EL spectra of undoped and doped BUBD-1 doped devices.

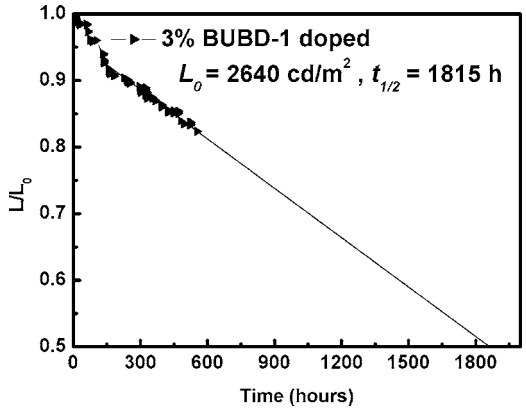

FIG. 4. Device operational stability for 3% BUBD-1 doped device.

and 466 nm, respectively. The spectrum of the undoped device is broad and featureless. The doped devices show a more greenish blue color due to the dopant BUBD-1 fluorescence and the $CIE_{x,y}$ coordinates are (0.16, 0.30) and (0.17, 0.33). The EL radiance efficiency of the 3% doped cell (0.05 W/A) is considerably higher than that of the undoped cell (0.018 W/A) due to the apparent higher fluorescence quantum yield of BUBD-1:MADN doped emission layer.[8] The external quantum efficiency (EQE) of the 3% doped device (6.5%) is also far higher than that of the undoped (2%) and 8% doped device (4.6%).

After encapsulation in the nitrogen dry box, the 3% BUBD-1 doped device under a constant current density of 20 mA/cm^2 with L_0=2640 cd/m^2 dropped to about 2180 cd/m^2 after operating continually for 676 h and the driving voltage has increased 1.2 V, as shown in Fig. 4. Assuming the scalable law of Coulombic degradation[16] and by estimation of its extrapolated profile, driving at a normalized L_0 value of 100 cd/m^2, the $t_{1/2}$ of the 3% BUBD-1 doped device without consideration of any accelerating factor[17] for blue device is projected to be 48 000 h.

In summary, we have demonstrated a highly efficient and stable device with the sky blue dopant BUBD-1 doped in MADN guest/host system. This sky blue device performance is among the best ever reported in the literature. The high EQE (6.5%) of this device also illustrates the excellent carrier recombination as well as the balance of holes and electrons in the emissive layer. The simple device structure and convenient fabrication process make it particularly attractive for industrial applications.

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[1] J. Kido, K. Nagai, and K. Okutama, Appl. Phys. Lett. **64**, 815 (1994).
[2] P. Destruel, P. Jolinat, R. Clergereaux, and J. Farenc, J. Appl. Phys. **85**, 397 (1999).
[3] D. Gupta and M. Katiyar, Opt. Mater. (Amsterdam, Neth.) **28**, 295 (2006).
[4] M. Li, W. L. Li, J. H. Niu, B. Chu, B. Li, X. Y. Sun, Z. Q. Zhang, and Z. Z. Hu, Solid-State Electron. **49**, 1956 (2005).
[5] Y. S. Wu, S. W. Hwang, H. H. Chen, M. T. Lee, W. J. Shen, and C. H. Chen, Thin Solid Films **488**, 265 (2005).
[6] M. T. Lee, H. H. Chen, C. H. Liao, C. H. Tsai, and C. H. Chen, Appl. Phys. Lett. **85**, 3301 (2004).
[7] K. Suzuki, A. Seno, H. Tanabe, and K. Ueno, Synth. Met. **143**, 89 (2004).
[8] J. Shi and C. W. Tang, Appl. Phys. Lett. **80**, 3201 (2002).
[9] Y. H. Kim, D. C. Shin, S. H. Kim, C. H. Ko, H. S. Hu, Y. D. Chae, and S. K. Kwon, Adv. Mater. (Weinheim, Ger.) **13**, 1690 (2001).
[10] C. Hosokawa, H. Higashi, H. Nakamura, T. Kusumoto, Appl. Phys. Lett. **67**, 3853 (1995).
[11] C. C. Yeh, M. T. Lee, H. H. Chen, and C. H. Chen, J. Soc. Inf. Disp. **35**, 789 (2004).
[12] A. Saitoh, N. Yamada, M. Yashima, K. Okinaka, A. Seno, K. Ueno, D. Tanaka, and R. Yashiro, J. Soc. Inf. Disp. **35**, 150 (2004).
[13] C. Hosokawa, H. Higashi, H. Nakamura, and T. Kusumoto, Appl. Phys. Lett. **67**, 3853 (1995).
[14] J. M. Kauffman and G. Moyna, J. Org. Chem. **68**, 839 (2003).
[15] J. Littman and P. Martic, J. Appl. Phys. **72**, 3610 (1992).
[16] S. A. Van Slyke, C. H. Chen, and C. W. Tang, Appl. Phys. Lett. **69**, 2160 (1996).
[17] H. Aziz, Z. D. Popovic, and N. X. Hu, Appl. Phys. Lett. **81**, 370 (2002).