A novel benzo[4,5]furo[3,2-d]pyrimidine-based host as a n-type host for blue phosphorescent organic light-emitting diodes

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ABSTRACT An electron-transport-type host was synthesized using a benzo[4,5]furo[3,2-d]pyrimidine (BFP) core to develop a high triplet energy host. The host was designed to have both the tetraphenylsilyl blocking group and the hole-transport-type carbazole group. In the device application, the host was used as an electron-transport-type host mixed with a hole-transport-type 3,3'-di(9H-carbazol-9-yl)-1,1'-biphenyl (mCBP) host in the blue phosphorescent organic light-emitting diodes (PhOLEDs) doped with a [[5-(1,1-dimethylethyl)-3-phenyl-1H-imidazo[4,5-b]pyrazin-1-yl-2(3H)-ylidene]-1,2-phenylene]bis-[[6-(1,1-dimethylethyl)-3-phenyl-1H-imidazo[4,5-b]pyrazin-1-yl-2(3H)-ylidene]-1,2-phenylene]iridium ($\text{Ir}(\text{cb})_3$) blue phosphor. As a result, the mCBP:CzBFPmSi mixed host showed high external quantum efficiency over 20% at 1000 cd m^{-2} and low efficiency roll-off in the blue PhOLEDs.

Keywords: blue device, host, efficiency, lifetime

INTRODUCTION

Organic light-emitting diodes (OLEDs) have been developed over the past few decades due to their advantages such as low power consumption, wide viewing angle, high brightness, high color purity and possibility of fabrication on various substrates [1–6]. At first, only fluorescent emitters which can show maximum internal quantum efficiency (IQE) of 25% were used, but the low IQE of them enforced the development of phosphors which can achieve IQE of 100% by the inter-system crossing mechanism using spin-orbit coupling of heavy atoms. Currently, organic phosphors are being mostly developed in the OLED industry due to their high efficiency exceeding that of fluorescent materials [7–17].

The high efficiency of the phosphors can be realized using the device platform employing a host-guest system which is an efficient method for improving the device performances. It can suppress the triplet exciton-induced quenching processes while reducing the intermolecular interaction between the phosphorescent emitters. In addition, the host matrix with good carrier transport ability facilitates the control of carrier balance and widens the exciton recombination zone, which enables superior device performances in phosphorescent OLEDs (PhOLEDs) [18–20]. There are several requirements for developing the host materials for PhOLEDs. Firstly, the host material must have higher triplet energy than phosphorescent emitters to prevent back energy transfer. Secondly, the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital

(LUMO) should be matched well with the energy levels of the carrier transport layers and phosphorescent emitters. Small energy barriers allow efficient injection of holes and electrons, which can reduce the turn-on and driving voltages (V_d) of the devices. Thirdly, good carrier transport property is necessary for balanced hole and electron density and enlarged exciton recombination zone in the emitting layer. Lastly, the thermal stability of host materials is important when fabricating and operating the device [21–23].

Many host materials for red and green PhOLEDs have been developed, but the hosts for blue PhOLEDs have not been popular because they must have high triplet energy to cover the high emission energy of blue phosphors. The triplet energy of the blue phosphors for PhOLEDs is around 2.8 eV, indicating that the host materials should have high triplet energy at least above 2.9 eV [24,25]. However, it has been challenging to develop the high triplet energy host. Especially, the development of high triplet energy electron transport (n-type) hosts was challenging despite the importance of n-type hosts as the main component of mixed host system consisting of hole transport (p-type) and n-type hosts.

Conventionally, electron-deficient moieties have been included in the n-type hosts for electron transport property and control of the LUMO level for electron injection. As the electron-deficient moieties of n-type hosts, phosphine oxide, pyridine, pyrimidine and triazine have been mostly used. The phosphine oxide derivatives such as 4,4'-bis(diphenylphosphine oxide)biphenyl (PO1), diphenylphosphine oxide-4-(triphenylsilyl)phenyl (TSPO1), and 2,8-bis(diphenylphosphine oxide) dibenzofuran (PODBF) are representative n-type host materials [26–28]. The phosphine oxide moiety works as a conjugation breaking group, resulting in high triplet energy. However, they are not suitable for fabricating stable blue PhOLEDs due to the instability of phosphine oxide caused by poor stability under photo-oxidation or low bond dissociation energy [13]. Another approach to develop the n-type hosts is to introduce hetero-aromatic rings like pyridine, pyrimidine and triazine as an alternative way to achieve high triplet energy and good stability. Among them, the triazine-derived hosts perform well as the hosts of blue PhOLEDs for improved efficiency and device operational lifetime [29–31]. However, pyrimidine-derived hosts have not been diverse although several pyrimidine derivatives offer high efficiency.

Herein, we report a novel host named 4-(9H-carbazol-9-yl)-2-(3-(triphenylsilyl)phenyl)benzo[4,5]furo[3,2-d]pyrimidine (CzBFPmSi) with a benzo[4,5]furo[3,2-d]pyrimidine (BFP) core.

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The CzBFPmSi was designed to have a hole-transport-type carbazole group, a tetraphenylsilyl blocking group and electron-transport-type BFP to develop a high-triplet-energy n-type host. In the device application, the host was used as the n-type host mixed with a p-type 3,3'-di(9H-carbazol-9-yl)-1,1'-biphenyl (mCBP) host in the blue PhOLEDs doped with a [[5-(1,1-dimethylethyl)-3-phenyl-1H-imidazo[4,5-b]pyrazin-1-yl-2(3H)-ylidene]-1,2-phenylene]bis[[6-(1,1-dimethylethyl)-3-phenyl-1H-imidazo[4,5-b]pyrazin-1-yl-2(3H)-ylidene]-1,2-phenylene]iridium (Ir(cb)₃) blue phosphor. It was demonstrated that the mCBP:CzBFPmSi mixed host achieved high external quantum efficiency (EQE) over 20% at 1000 cd m⁻² in the blue PhOLEDs.

RESULTS AND DISCUSSION

Host design and synthesis

The CzBFPmSi is an n-type host material with substituted carbazole and tetraphenylsilyl unit around a benzo[4,5]furo[3,2-d]pyrimidine (BFP) core. The BFP core can have good electron transport characteristics because of a large electron deficiency by the pyrimidine unit. The tetraphenylsilyl unit incorporated in the CzBFPmSi structure has weak electron withdrawing characteristics by the hyperconjugation effect and can strengthen the electron transport property of the BFP core [32]. Moreover, its bulky structure inhibits intermolecular interactions, allowing CzBFPmSi to maintain the high triplet energy in solid state. The electron-rich carbazole was introduced for the stability of the material by relieving the degradation of the host when hole leakage occurs from the p-type host to CzBFPmSi.

In our previous study, we studied the relationship between the substitution pattern and photophysical properties of benzo[4,5]-thieno[3,2-d]pyrimidine (BTP) derivatives which have a sulfur atom instead of the oxygen atom of BFP [34]. The previous work revealed that the 4-(9H-carbazol-9-yl)-2-(3-(triphenylsilyl)phenyl)benzo[4,5]furo[3,2-d]pyrimidine (CzBTPmSi) with the carbazole at the 4 position and tetraphenylsilyl unit at the 2 position showed high triplet energy for triplet exciton harvesting of Ir(cb)₃. However, the triplet energy of the CzBTPmSi host was not high enough to completely harness the triplet excitons of Ir(cb)₃. Therefore, the CzBFPmSi borrowed the main skeleton from CzBTPmSi and replaced sulfur with oxygen for enlarged triplet energy. The high electronegativity and small size of oxygen relative to those of sulfur may increase the triplet energy of the host and overcome the EQE limit of the CzBTPmSi in our previous work.

The synthesis process of CzBFPmSi is shown in Scheme 1.

Scheme 1 Synthesis route of CzBFPmSi.

Firstly, the carbazole unit was introduced at the 4 position of the BFP core through a Buchwald-Hartwig coupling reaction since the 4 position of the core is more reactive than the 2 position as reported in previous work [33]. Then, the tetraphenylsilyl group was attached to the 2 position of BFP using dioxaborolane-functionalized tetraphenylsilane [32] through a Suzuki-Miyaura coupling reaction. The final product was thoroughly purified by silica gel column chromatography, recrystallization and vacuum sublimation to remove impurities. The purity of the final product was over 99.9% from high-performance liquid chromatography (HPLC) analysis. Identification and confirmation of the final compounds were carried out using chemical analytical methods such as ¹H and ¹³C nuclear magnetic resonance (NMR) spectrometry and mass spectrometry (MS).

Frontier orbital calculation and photophysical properties

The HOMO and LUMO electronic simulation of CzBFPmSi was performed using the B3LYP 6-31G(d) basis set of the Gaussian 16 software package to predict the molecular geometry and photophysical properties (Fig. 1). The HOMO was mainly distributed over carbazole and slightly expanded to the BFP core due to steric hindrance between carbazole and the BFP core. Nevertheless, the LUMO distribution was governed by the electron-poor BFP core. Since the 2 position of the BFP core is a node of the LUMO, the LUMO did not expand to the tetraphenylsilyl group although it has a planar geometry due to the hydrogen bonding between nitrogen of the pyrimidine and hydrogen of the phenyl unit. The theoretical HOMO/LUMO energy level of CzBFPmSi was -5.60/-1.75 eV.

The basic photophysical characteristics of the CzBFPmSi host was analyzed to investigate the potential as a host of blue PhOLEDs. The ultraviolet-visible (UV-vis) absorption and fluorescence/phosphorescence spectra at a low temperature of 77 K in tetrahydrofuran (THF) solution were measured to understand the photophysical properties of the CzBFPmSi host (Fig. 2). The UV-vis absorption spectrum of the CzBFPmSi host reflected a strong π - π^* absorption of the backbone structure with an absorption onset energy of 3.28 eV. The photoluminescence (PL) spectrum of the CzBFPmSi in the THF solution at 77 K delivered a singlet energy (E_s)/triplet energy (E_T) of 3.40/3.09 eV, from the onset energy of the emission spectrum. Compared with CzBTPmSi (singlet energy/triplet energy of 3.29/2.88 eV), the triplet energy was increased by about 0.2 eV because of the high electronegativity and small size of oxygen atom. The increased triplet energy may make the energy transfer from CzBFPmSi to a blue-emitting phosphor with a triplet

Figure 1 The optimized structures and HOMO and LUMO distributions of the CzBFPmSi host.

Figure 2 UV-vis absorption spectrum at room temperature, low-temperature fluorescence (LTFI) and low-temperature phosphorescence (LTPH) spectra in THF solution at 77 K of the CzBFPmSi host.

energy of 2.80 eV as a host material.

Electrochemical and thermal properties

The HOMO and LUMO of CzBFPmSi were measured using cyclic voltammetry (CV). The HOMO/LUMO energy level of CzBFPmSi was $-6.34/-3.07$ eV, slightly shallower than that of CzBTPmSi ($-6.39/-3.15$ eV) (Fig. S1). The HOMO/LUMO level of CzBFPmSi was deep because of strong electron withdrawal characteristics of an electron deficient BFP core.

The thermal stability of CzBFPmSi was also evaluated. As displayed in Fig. S2, the glass transition temperature (T_g) of the CzBFPmSi appeared at 116°C in the differential scanning calorimetry (DSC) heating cycle. From thermogravimetric analysis (TGA), the thermal decomposition temperature (T_d) of CzBFPmSi at 5% weight loss was found to be 418°C from the heating scan at a heating rate of $10^\circ\text{C min}^{-1}$ under nitrogen. The DSC and TGA data demonstrate superior thermal stability of

CzBFPmSi resulting from the rigid nature of the conjugated backbone structure which would not undergo decomposition during thermal evaporation and device operation. The photo-physical, electrochemical and thermal properties of CzBFPmSi and CzBTPmSi are summarized in Table 1.

Device applications

In the device application, the CzBFPmSi was used as the n-type host mixed with a p-type 3,3'-di(9H-carbazol-9-yl)-1,1'-biphenyl (mCBP) host. To confirm the exciplex formation between mCBP and CzBFPmSi, the PL of the mixed host was measured by mixing the two hosts at a ratio of 1:1. The PL spectra of each host and the mixed host are shown in Fig. S3. Compared with the PL spectrum of each host, only the emission of the low energy CzBFPmSi was observed in the mixed host. This indicates that the mixed host of the mCBP:CzBFPmSi was an exciplex-free type host. A blue-emitting $\text{Ir}(\text{cb})_3$ phosphor was doped as a blue phosphorescent emitter in the mixed host to assess the performances of CzBFPmSi as the n-type host. The device consisted of the following structures for the device performance measurement: ITO (50 nm)/BCFN:HATCN (40 nm, HATCN 30%)/BCFN (10 nm)/mCBP (10 nm)/mCBP:CzBFPmSi (25 nm, 50%:50%)/DBFTrz (5 nm)/ZADN (20 nm)/LiF (1.5 nm)/Al (200 nm). The mixed host was doped with an $\text{Ir}(\text{cb})_3$ phosphorescent emitter at a doping concentration of 20%. The mixing ratio of the mCBP:CzBFPmSi host was 50:50 through optimization of the host ratio (Fig. S4 and Table S1). The device lifetime and EQE roll-off of the devices were optimized at the 50:50 host composition. The device structure and the molecular structure of the materials including CzBTPmSi are shown in Fig. 3.

Electroluminescence (EL) spectrum, current density–voltage–luminance, EQE–luminance, and device lifetime of the blue PhOLEDs are displayed in Fig. 4. In the EL spectrum, all devices showed similar emission spectrum and color coordinates (CIEs)

Table 1 Physical properties of CzBFPmSi and CzBTPmSi.

Compounds	Maximum absorption peak (nm)	E_s (eV)	E_T (eV)	HOMO/LUMO (eV)	E_g^a (eV)	T_g ($^\circ\text{C}$)	T_d ($^\circ\text{C}$)
CzBFPmSi	350	3.40	3.09	$-6.34/-3.07$	3.54	116	418
CzBTPmSi	383	3.29	2.88	$-6.39/-3.15$	3.24	124	445

a) Optical band gap (E_g) was estimated from the onset wavelength of the UV-vis absorption spectrum.

Figure 3 Device structure with HOMO and LUMO levels and the molecular structure of the materials.

Figure 4 Device performances of the 20% Ir(cb)₃-doped mCBP:CzBFPmSi and mCBP:CzBTPmSi devices. (a) EL spectrum of blue PhOLEDs, (b) current density (*I*)–voltage–luminance, (c) EQE–luminance, (d) device lifetime data at 100 cd m^{−2}.

of (0.14, 0.17), suggesting that the EL emission comes from Ir(cb)₃ with little contribution from the n-type host. The EL spectrum of the CzBFPmSi device was similar to the PL spectrum of the mCBP: CzBFPmSi: Ir(cb)₃ film (Fig. S5), suggesting energy transfer from the mixed host to the phosphor. The driving voltages at 1 cd m^{−2}/1000 cd m^{−2} of CzBFPmSi and CzBTPmSi devices were observed as 3.0/5.4 V, 3.0/5.2 V, respectively. Both materials had similar LUMO energy levels for electron injection, resulting in no difference of turn-on voltage. However, the mCBP:CzBFPmSi device demonstrated higher maximum EQE of 21.8% than 18.6% of the mCBP:CzBTPmSi

device. The increment of the EQE in the mCBP:CzBFPmSi device is correlated with the triplet energy of the hosts. The triplet energy of CzBFPmSi was higher than that of CzBTPmSi by 0.2 eV and was high enough to harvest triplet excitons of the Ir(cb)₃ emitter. In the case of CzBTPmSi, relatively low triplet energy could not fully harness all excitons of Ir(cb)₃, degrading the maximum EQE. The EQE roll-off at 1000 cd m^{−2} was also improved by employing the CzBFPmSi host in place of CzBTPmSi. Moreover, the mixed host device of mCBP: CzBFPmSi was better than the single host device of CzBFPmSi in terms of EQE roll-off (Fig. S6).

Table 2 Summarized the device performances of the Ir(cb)₃-doped mCBP:CzBFPmSi and mCBP:CzBTPmSi devices

Devices	V _d (V)	I (mA cm ⁻²)	CIE (x, y)	EQE/EQE _{max} (%)	PE ^a /PE _{max} (lm W ⁻¹)	CE ^a /CE _{max} (cd A ⁻¹)	Lifetime ^b (h)
mCBP:CzBFPmSi	5.4	3.8	0.14, 0.17	20.5/21.8	15.8/23.4	26.8/24.8	1272
mCBP:CzBTPmSi	5.2	4.9	0.14, 0.18	15.6/18.6	12.5/23.2	20.6/24.8	1086

a) PE: power efficiency; CE: current efficiency, at luminance of 1000 cd m⁻². b) LT50, device lifetime at 100 cd m⁻².

As the lifetime is one of the most important factors in blue PhOLEDs, the device lifetime was measured under the constant current density driving condition. The device operational lifetime of the blue PhOLEDs at 100 cd m⁻² was quite similar in the mCBP:CzBFPmSi and mCBP:CzBTPmSi devices, suggesting that the CzBFPmSi and CzBTPmSi are equivalent in terms of host stability for stable operation of blue PhOLEDs. The change of sulfur with oxygen enhanced EQE of the blue PhOLEDs with the help of increased triplet energy while maintaining the same level of stability of the CzBTPmSi host [34]. All device data are summarized in Table 2. The use of CzBFPmSi in the mixed host with mCBP was more effective than single host to extend the device lifetime (Fig. S6).

CONCLUSIONS

The CzBFPmSi was developed as a high-triplet-energy host of blue PhOLEDs using a BFP core which can play a role of an electron transport unit. Compared with the CzBTPmSi host with BTP instead BFP, the CzBFPmSi host presented high triplet energy of 3.09 eV and accompanying triplet exciton harvesting of blue-emitting Ir(cb)₃. The blue PhOLEDs employing a mixed host of mCBP:CzBFPmSi and Ir(cb)₃ phosphor afforded maximum EQE/EQE at 1000 cd m⁻² of 21.8%/20.5% with the same color coordinate of (0.14, 0.17) without damaging the device operational lifetime. This work demonstrated the potential of the BFP as an n-type core of the electron-transport-type host and guided the design approach of the n-type host for high EQE in the blue PhOLEDs.

Received 15 July 2021; accepted 21 September 2021;
published online 22 October 2021

- Tang CW, VanSlyke SA. Organic electroluminescent diodes. *Appl Phys Lett*, 1987, 51: 913–915
- Mitschke U, Bäuerle P. The electroluminescence of organic materials. *J Mater Chem*, 2000, 10: 1471–1507
- Müller CD, Falcou A, Reckefuss N, *et al.* Multi-colour organic light-emitting displays by solution processing. *Nature*, 2003, 421: 829–833
- Reineke S, Lindner F, Schwartz G, *et al.* White organic light-emitting diodes with fluorescent tube efficiency. *Nature*, 2009, 459: 234–238
- Uoyama H, Goushi K, Shizu K, *et al.* Highly efficient organic light-emitting diodes from delayed fluorescence. *Nature*, 2012, 492: 234–238
- Zhang Q, Li B, Huang S, *et al.* Efficient blue organic light-emitting diodes employing thermally activated delayed fluorescence. *Nat Photon*, 2014, 8: 326–332
- Baldo MA, O'Brien DF, You Y, *et al.* Highly efficient phosphorescent emission from organic electroluminescent devices. *Nature*, 1998, 395: 151–154
- Baldo MA, Lamansky S, Burrows PE, *et al.* Very high-efficiency green organic light-emitting devices based on electrophosphorescence. *Appl Phys Lett*, 1999, 75: 4–6
- Adachi C, Baldo MA, Thompson ME, *et al.* Nearly 100% internal phosphorescence efficiency in an organic light-emitting device. *J Appl Phys*, 2001, 90: 5048–5051
- Adachi C, Baldo MA, Forrest SR, *et al.* High-efficiency red electrophosphorescence devices. *Appl Phys Lett*, 2001, 78: 1622–1624
- Lamansky S, Djurovich P, Murphy D, *et al.* Highly Phosphorescent bis-cyclometalated iridium complexes: synthesis, photophysical characterization, and use in organic light emitting diodes. *J Am Chem Soc*, 2001, 123: 4304–4312
- Udagawa K, Sasabe H, Cai C, *et al.* Low-driving-voltage blue phosphorescent organic light-emitting devices with external quantum efficiency of 30%. *Adv Mater*, 2014, 26: 5062–5066
- Lin N, Qiao J, Duan L, *et al.* Molecular understanding of the chemical stability of organic materials for OLEDs: A comparative study on sulfonyl, phosphine-oxide, and carbonyl-containing host materials. *J Phys Chem C*, 2014, 118: 7569–7578
- Xu H, Chen R, Sun Q, *et al.* Recent progress in metal–organic complexes for optoelectronic applications. *Chem Soc Rev*, 2014, 43: 3259–3302
- Cao S, Hao L, Lai WY, *et al.* Distinct phosphorescence enhancement of red-emitting iridium(III) complexes with formyl-functionalized phenylpyridine ligands. *J Mater Chem C*, 2016, 4: 4709–4718
- Liu X, Yu Z, Yu M, *et al.* Iridium(III)-complexed polydendrimers for inkjet-printing OLEDs: The influence of solubilizing steric hindrance groups. *ACS Appl Mater Interfaces*, 2019, 11: 26174–26184
- Jiang Y, Lv P, Pan JQ, *et al.* Low-threshold organic semiconductor lasers with the aid of phosphorescent Ir(III) complexes as triplet sensitizers. *Adv Funct Mater*, 2019, 29: 1806719
- Chaskar A, Chen HF, Wong KT. Bipolar host materials: A chemical approach for highly efficient electrophosphorescent devices. *Adv Mater*, 2011, 23: 3876–3895
- Jou JH, Kumar S, Agrawal A, *et al.* Approaches for fabricating high efficiency organic light emitting diodes. *J Mater Chem C*, 2015, 3: 2974–3002
- Tao Y, Yang C, Qin J. Organic host materials for phosphorescent organic light-emitting diodes. *Chem Soc Rev*, 2011, 40: 2943–2970
- Dias FB, Bourdakos KN, Jankus V, *et al.* Triplet harvesting with 100% efficiency by way of thermally activated delayed fluorescence in charge transfer OLED emitters. *Adv Mater*, 2013, 25: 3707–3714
- Im Y, Byun SY, Kim JH, *et al.* Recent progress in high-efficiency blue-light-emitting materials for organic light-emitting diodes. *Adv Funct Mater*, 2017, 27: 1603007
- Sasabe H, Kido J. Development of high performance OLEDs for general lighting. *J Mater Chem C*, 2013, 1: 1699–1707
- Lee J, Chen HF, Batagoda T, *et al.* Deep blue phosphorescent organic light-emitting diodes with very high brightness and efficiency. *Nat Mater*, 2016, 15: 92–98
- Maheshwaran A, Sree VG, Park HY, *et al.* High efficiency deep-blue phosphorescent organic light-emitting diodes with CIE x, y (≤ 0.15) and low efficiency roll-off by employing a high triplet energy bipolar host material. *Adv Funct Mater*, 2018, 28: 1802945
- Burrows PE, Padmaperuma AB, Sapochak LS, *et al.* Ultraviolet electroluminescence and blue-green phosphorescence using an organic diposphine oxide charge transporting layer. *Appl Phys Lett*, 2006, 88: 183503
- Padmaperuma AB, Sapochak LS, Burrows PE. New charge transporting host material for short wavelength organic electrophosphorescence: 2,7-bis(diphenylphosphine oxide)-9,9-dimethylfluorene. *Chem Mater*, 2006, 18: 2389–2396
- Vecchi PA, Padmaperuma AB, Qiao H, *et al.* A dibenzofuran-based host material for blue electrophosphorescence. *Org Lett*, 2006, 8: 4211–4214
- Chen HF, Yang SJ, Tsai ZH, *et al.* 1,3,5-triazine derivatives as new electron transport-type host materials for highly efficient green phosphorescent OLEDs. *J Mater Chem*, 2009, 19: 8112–8118

- 30 Hung WY, Chiang PY, Lin SW, *et al.* Balance the carrier mobility to achieve high performance exciplex OLED using a triazine-based acceptor. *ACS Appl Mater Interfaces*, 2016, 8: 4811–4818
- 31 Inomata H, Goushi K, Masuko T, *et al.* High-efficiency organic electrophosphorescent diodes using 1,3,5-triazine electron transport materials. *Chem Mater*, 2004, 16: 1285–1291
- 32 Jung M, Lee KH, Lee JY, *et al.* A bipolar host based high triplet energy electrophosphorescent for an over 10 000 h lifetime in pure blue phosphorescent organic light-emitting diodes. *Mater Horiz*, 2020, 7: 559–565
- 33 Kim DS, Lee KH, Lee JY. Novel positive polaron stabilizing n-type host for high efficiency and long lifetime in blue phosphorescent organic light-emitting diodes. *ACS Appl Mater Interfaces*, 2020, 12: 19737–19745
- 34 Jeon SK, Lee HL, Yook KS, *et al.* Recent progress of the lifetime of organic light-emitting diodes based on thermally activated delayed fluorescent material. *Adv Mater*, 2019, 31: 1803524

Acknowledgements This work was supported by the Korea Institute for Advancement of Technology (KIAT) and the Ministry of Trade, Industry and Energy of Korea (P0017363 and 20012622).

Author contributions Lee JY and Ha J designed, synthesized and analyzed the CzBFPmSi host used in this study. Lim J fabricated the devices. The manuscript was prepared by Ha J and Lee JY. All authors reviewed and approved the final manuscript.

Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Experimental details and supporting data are available in the online version of the paper.

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