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TADF Technology for Efficient Blue OLEDs: Status and Challenges from an Industrial Point of View

Alhama Arjona-Esteban, Barbara Szafranowska and Julian Ochsmann

Abstract

The rise of OLED technology for display applications over the past decade was impressive. Today, OLED displays can be found everywhere, for example, in smartphones, TVs, smartwatches, monitors, cars, or digital cameras. However, as technology advances, the need for better OLED materials which help to improve energy efficiency and resolution of OLED displays is growing. While for the red and green pixels, phosphorescent materials have allowed for a boost in performance, the use of fluorescent materials for the blue pixel still limits the efficiency of OLED displays. Academic research has demonstrated many improvements regarding the efficiency of blue OLEDs using phosphorescent or TADF materials. However, studies on the limitations of device lifetime are rare. In the present chapter, the development of blue OLEDs based on TADF emitters is discussed from an industrial point of view. First, the material design principles for TADF molecules as well as the requirements for efficient blue TADF emitters are discussed. Moreover, a short literature overview on the latest improvements in blue TADF materials in academia and industry is presented. Finally, an outlook on this technology, its industrial possibilities, and alternatives is given.

Keywords: TADF, triplet up-conversion, industry, deep blue, high efficiency blue

1. Introduction

After their first development in the late 1980s [1], organic-light-emitting diodes slowly made their entry into the market of displays for televisions and mobile phones. Compared to other display technologies, OLED displays offer advantages such as wide viewing angles and very high contrast ratio while maintaining low energy consumption. In addition, OLED displays are thin and lightweight and can even be fabricated on flexible substrates, which allows for new and exciting applications. OLEDs can be produced using small molecules or polymers by vacuum thermal evaporation or by inkjet printing.

The basic pixels used to generate the primary colors, red, green, and blue, in an OLED display should have similar performance in order to guarantee a balanced efficiency and power consumption, which is beneficial for display technology, for example, in terms of increasing resolution and decreasing backplane technology complexity. However, as of today, the red and green pixels outperform the blue ones
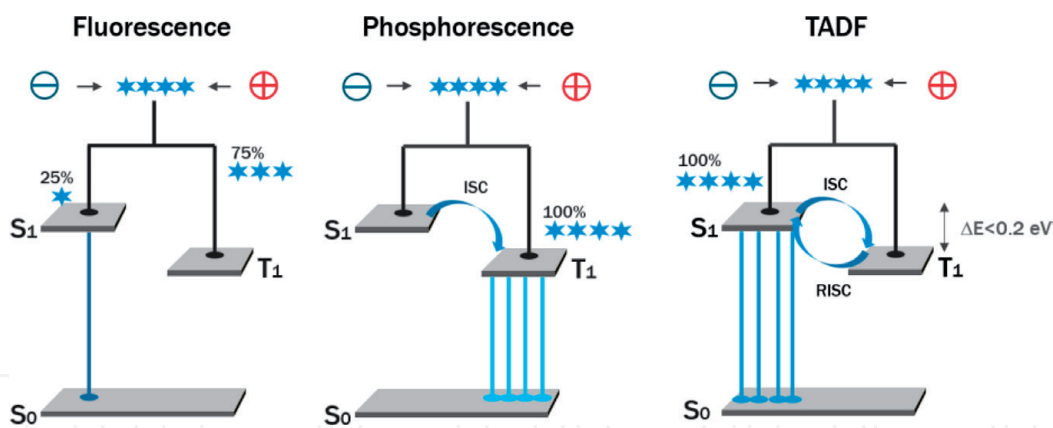
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Figure 1.
Schematic energy diagrams of fluorescent, phosphorescent, and TADF molecules and their corresponding excitation and de-excitation pathways, when used in OLEDs. Fluorescence often relates to the first emitter material generation. Phosphorescence is the second material generation. TADF marks the latest conceptual development. Figure courtesy of CYNORA.

by far, which lies in the different technologies used for the different colors: There are three main photophysical mechanisms, which are relevant for light generation in OLEDs: fluorescence, phosphorescence, and thermally activated delayed fluorescence (TADF). Fluorescent materials were the first to be used in OLEDs [2]. However, the efficiency of a simple OLED device based on fluorescent materials is limited. These materials can only convert 25% of the excitons formed under electronic excitation into light because quantum mechanics dictates that under electronic excitation, singlet and triplet excitons are formed in a ratio of 1:3 (see **Figure 1**). Thus, with the discovery of phosphorescent materials, which can make use of all the excited states including triplets, the efficiency of green and red OLEDs increased drastically [3, 4]. However, as of today, no deep blue phosphorescent materials have been found to be stable enough for industrial applications. In this regard, the third generation of OLED materials comes into play. TADF technology allows, like phosphorescent materials, for the conversion of all excitons into light, but holds the promise of longer device lifetime [5–11].

In this chapter, we will focus on TADF technology as a potential alternative to fluorescent materials in deep blue OLEDs. We will discuss the advantages of this technology and the challenges connected to entering the industrial production of displays.

2. Requirements for TADF behavior and key performance indicators of TADF emitters

In this section, we will focus on the main design principles for TADF molecules and discuss the parameters that make TADF emission possible and how to tune them.

In simple terms, thermally activated delayed fluorescence, as depicted in **Figure 1**, is a fluorescence mechanism based on the repopulation of the singlet state by reverse intersystem crossing (RISC) from the triplet state, triggered by thermal energy. Thus, the theoretical internal quantum yield (IQE) of an OLED based on TADF is 100%, comparable to that of phosphorescent emitters and much higher than the 25% achieved by fluorescent materials, neglecting any additional contributions from triplet-triplet annihilation (TTA).

For the TADF process to be possible, the energy difference between the triplet and the singlet states (ΔE_{ST}) has to be smaller than 0.2 eV [12]. From the molecular

design point of view, this small ΔE_{ST} is mostly addressed by spatially separating the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) of the molecule. The use of electron-donating (donor) and electron-withdrawing (acceptor) building blocks generates a charge-transfer structure with localized HOMO and LUMO orbitals. This localization can be favored by increasing the twist angle between the donor and acceptor moiety. However, a minimal overlap of the orbitals is necessary for RISC to take place, so a trade-off between small ΔE_{ST} and overlap has to be found.

Besides having a small ΔE_{ST}, an efficient TADF emitter has to fulfill other requirements: High photoluminescence quantum yields (PLQY) together with short excited state lifetimes ensure efficient RISC and radiative decay from the singlet state. Furthermore, a narrow spectrum at the desired color coordinate is necessary to provide the requested color purity. In addition, and especially for industrial applications, a long-lived device has to be delivered in order to satisfy the customers.

2.1 Color tuning: how to achieve blue

The use of strong donor and acceptor units is very widespread when aiming for small ΔE_{ST} and short excited state lifetime. However, in order to achieve blue emission, the electron-donor and acceptor units have to be carefully matched.

Since the frontier molecular orbitals (FMOs) in TADF emitters are highly localized on the donor and acceptor moieties, it can be assumed that the FMOs of the emitters will be very similar to the FMOs of the isolated donor and acceptor building blocks. Hence, the HOMO of the TADF emitter is determined by the donor moiety and the LUMO by the acceptor moiety (see **Figure 2**).

We can get an estimate on the donor and acceptor strength of different building blocks by performing density functional theory (DFT) calculations and comparing their HOMO and LUMO values. A higher HOMO level (less negative) corresponds to a stronger donor, while a strong acceptor has a lower LUMO level
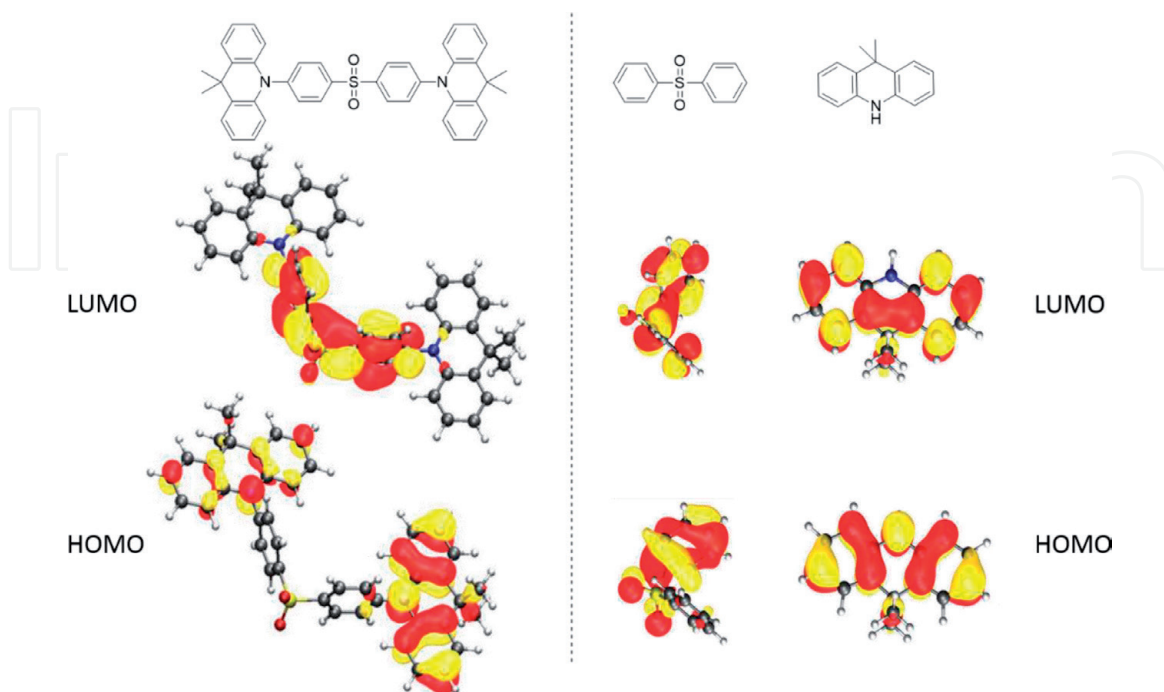

Figure 2.
The calculated FMO levels of the TADF emitter depicted on the left can be attributed to the respective HOMO (donor) and LUMO (acceptor) of the building blocks depicted on the right.

(more negative) (see **Figure 3**). A detailed list of the calculated HOMO and LUMO levels of many donor and acceptor building blocks has been published elsewhere [10].

Finally, from the difference between the calculated HOMO and LUMO levels, we can get a rough estimate of the optical bandgap, which corresponds to the combination of these donor and acceptor moieties. Carefully choosing the donor and acceptor units based on the calculations will allow us to reach the desired color range, in this case, deep blue with peak emission between 450 and 470 nm.

2.2 Narrow emission

Typically, TADF emitters display broad emission spectra. The reason is that the intramolecular charge-transfer (CT) state, where the emission originates, can undergo geometric relaxation, leading to many molecular configurations emitting at different energies. While for lighting applications, this intrinsic property of TADF emitters can be seen as an advantage, for display applications, the broad emission should be avoided. The display industry requires high color purity with CIEy values around 0.1 for the blue pixel, which can, with current host materials, only be achieved with a narrow spectrum. Moreover, when the spectrum is narrow, the emission onset can be shifted to lower energies, improving the blue color. Shifting the emission onset to lower energies is beneficial in matching the emitter with available host materials and getting a higher stability of the whole system (see Section 4: Requirements for host materials).

The host material can also influence the width and position of the spectrum of the TADF emitter. Polar hosts, for instance, often lead to broader and red-shifted spectra [13]. However, this effect is small in comparison to the intrinsic variations of the different emitter families [14]. Therefore, it is worth aiming to produce molecular structures that have an intrinsically smaller full width at half maximum (FWHM). In the literature, this is mainly addressed by rigidification of the donor-acceptor scaffold in order to minimize the rotational and bending modes and thereby suppressing the geometric relaxation of the CT state [10]. The rigidity can
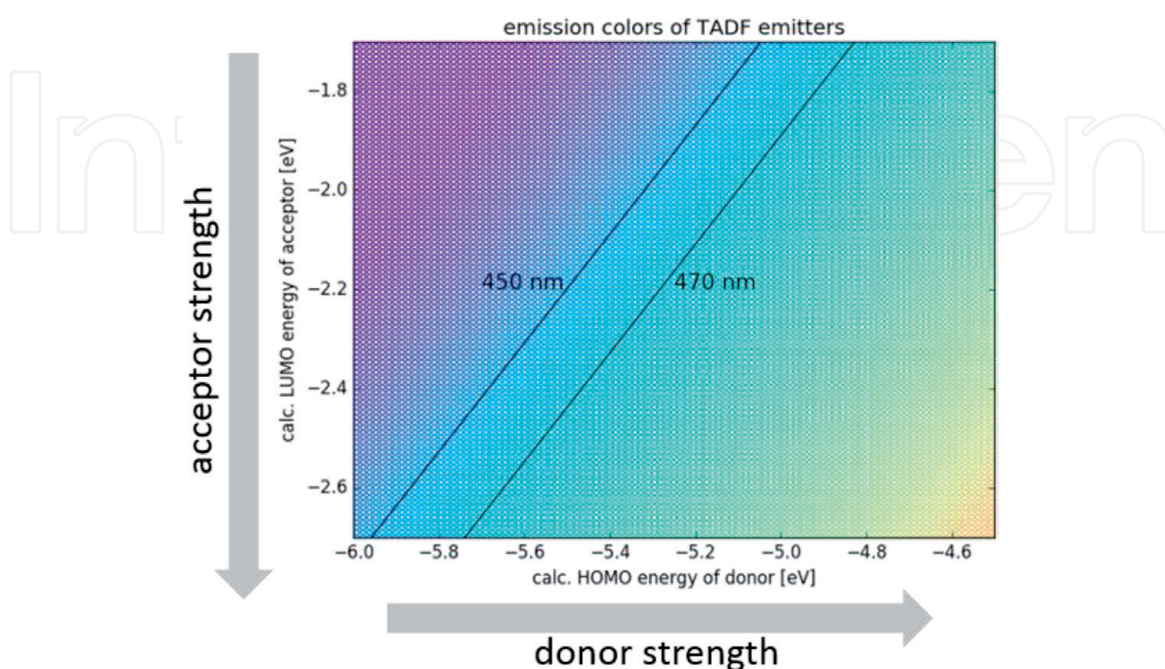

Figure 3.
Correlation of calculated HOMO and LUMO values of donor and acceptor building blocks with the expected emission color of the resulting TADF emitter. Figure courtesy of CYNORA.

be obtained by fusing the donor and acceptor units or introducing steric hindrances, as demonstrated in Ref. [15] by interlocking the donor units.

2.3 Tuning the excited state dynamics of TADF emitters

The main parameters which describe the excited state dynamics of TADF emitters are the fluorescence radiative decay rate k_F, the rate of delayed fluorescence k_{DF}, the rates of intersystem crossing k_{ISC}, and reverse intersystem crossing k_{RISC}, as well as the energy difference ΔE_{ST} between the first excited singlet S_1 and the first excited triplet T_1 states (see **Figure 4**). In order to obtain the best performing TADF emitters, all of these parameters have to be taken into account and careful molecular design must go hand in hand with in-depth photophysical analysis of these emitter systems.

The light-emitting performance of TADF materials depends on efficient radiative decay processes (k_F and k_{DF}) from S_1 to the electronic ground state S_0 and is also closely related to ΔE_{ST}, which governs the up-conversion of excitons from T_1 to S_1. A small ΔE_{ST} is crucial to obtain high values of k_{RISC}, improving the triplet harvesting through the thermally activated reverse intersystem crossing mechanism.

Decreasing the singlet-triplet energy gap ΔE_{ST} and increasing the radiative decay rate k_F is a useful way to get efficient TADF emission. Unfortunately, as mentioned at the beginning of Section 2, there is a trade-off between getting a small ΔE_{ST} and getting a high k_F, which is related to the electronic coupling between the ground state and the singlet excited state. A good separation of the HOMO and LUMO orbitals leads to a small ΔE_{ST}, but it also reduces k_F [16]. On the contrary, compounds with overlapping HOMO and LUMO orbitals are expected to exhibit high values for k_F, but yielding relatively large ΔE_{ST}, and thus showing less TADF contribution [17].

One of the approaches to increase the radiative decay rate, while maintaining a small ΔE_{ST} in TADF emitters, is the concept of using an aromatic bridge or spacer between the donor and acceptor moieties in the molecular design. In such a system, the delocalization of molecular orbitals is given, while there is in addition a weak overlap of HOMO and LUMO orbitals at the spacer, which induces a larger oscillator strength, enhancing the rate of radiative decay. This concept was successfully demonstrated in many TADF emitters containing phenyl linkers between donor and acceptor units in one TADF molecule [17–20]. Initially, the aromatic bridge negatively influenced ΔE_{ST}—making it larger—because of an increased S_1 energy level, whereas the T_1 level was reduced by the extended π-conjugation. But in such cases, the singlet-triplet energy gap could still be reduced by using stronger donors and acceptors and thereby strengthening the charge-transfer character [21–23]. In addition, the π-conjugation can be interrupted by twisting the donor and acceptor
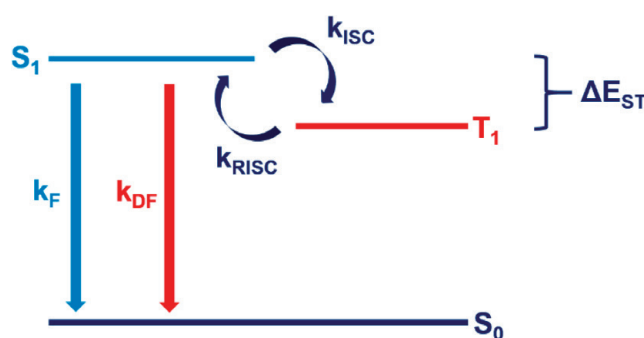

Figure 4.
Schematic energy diagram showing the main parameters which determine the excited state dynamics of TADF emitters.

units, so that they are nearly orthogonal to each other. This design strategy is also very beneficial in decreasing ΔE_{ST} and hence increasing k_{RISC}.

Other approaches reported in the literature to get highly efficient TADF materials are to delocalize the HOMO by increasing the number of donors [10, 18, 20] or to design a dual emitting core [24, 25]. In the second case, light absorption and emission is intensified by introducing multiple TADF chromophores fused into one molecule, yielding high PLQY.

The rate of reverse intersystem crossing k_{RISC} is directly linked to the easily observable excited state lifetime of delayed fluorescence τ_{DF}, which is usually in the order of a few microseconds for efficient TADF molecules. The higher the k_{RISC}, the shorter is τ_{DF}. τ_{DF} is a measure for how long on average the triplet excited state of the TADF emitter is populated. Long-lived triplet excitons are believed to be destructive for OLED devices, because they enable potentially detrimental processes such as triplet-triplet or triplet-polaron annihilation [26–29]. Therefore, triplet excited state lifetimes of TADF emitters should be as short as possible to enhance device stability by reducing detrimental quenching processes. Again, the reduction of the ΔE_{ST} gap results in speeding up the triplet harvesting mechanism. Several new molecular design methods have been proposed to reach an excited state lifetime of only a few microseconds, including physical separation of donor and acceptor units, dual emitting cores, breaking conjugation by twisted structures, multi-donor approach, introduction of strong donors and acceptors, and others described above [30, 31].

3. Blue TADF emitters in the literature

The general approach followed in the literature for the design of TADF emitters consists in combining donor and acceptor moieties into one molecule to separate the HOMO and LUMO orbitals and ensure a small ΔE_{ST} value. In this section, the latest developments reported in the literature since 2017 are collected and classified by

Compound	PI	Performance	Group
Sf-3Cz	Fan, Liao and coworkers [36]	15% EQE at 100 cd/m^2 CIE (0.16, 0.14)	Sulfone
G2	Xu and coworkers [35]	(no EQE) CIE (0.15, 0.12)	Sulfone
3DpYM-pDTC	Cheng and coworkers [37]	20% EQE at 500 cd/m^2 CIE (0.14, 0.18)	Ketone
TXAZ	Kim, Kim and coworkers [38]	16% EQE max (DPEPO) CIE (0.15, 0.13)	Triazine
FATA	Kaji and coworkers [34]	11% EQE max CIE (0.15, 0.13)	Triazine
Ac3MHPM	Kido and coworkers [39]	10% EQE at 100 cd/m^2 CIE (0.16, 0.15)	Pyrimidine
CNICtCz	Lee and coworkers [40]	10% EQE at 100 cd/m^2 CIE(0.14, 0.13)	Nitrile
DCzBN3	Adachi and coworkers [41]	10% EQE at 100 cd/m^2 CIE (0.15, 0.06)	Nitrile
TN4T-PCZ	Zheng, Meng and coworkers [33]	20% EQE max CIE (0.16, 0.03)	CF3-pyridine

Table 1.
Status of deep-blue TADF technology as published in the literature.

Figure 5.
Selected structures of published deep-blue TADF emitters.

the acceptor unit. We have focused on efficient devices (EQE > 10%) with deep-blue color (CIEy < 0.15). The references are collected in **Table 1** and **Figure 5**. For earlier results, we recommend other review articles [9–11, 32]. Most of the collected articles put their main focus on achieving deep blue color by combining donor units based on carbazole or acridine motifs and acceptors such as sulfones, triazines, or pyrimidines. While high EQE values can be achieved [33], these data have to be taken with care, since often they are given at low luminance (10–100 cd/m^2) and the devices suffer from high roll-off. Unfortunately, very few data are provided on device stability.

Interestingly, many approaches aim for solution-processed OLEDs either using small molecules bearing solubilizing chains [34] or dendrimer structures [35]. Currently, the vast majority of OLED products issued from the display industry are based on the evaporation of small molecules under vacuum. Printing and coating techniques are however receiving increasing attention due to the evident advantages of cost-effectivity and low material consumption.

4. Requirements for host materials

It is commonly known that the performance of TADF emitters is often very poor in neat emitter films, because of concentration quenching, aggregation, and other effects. Therefore, diluting the emitter molecules with host molecules at relatively low emitter concentrations (10–30%) improves not only their photophysical

characteristics but also boosts the efficiency in devices [42]. One of the basic requirements for a host material is a sufficiently high triplet state energy. In fact, the T_1-state of the host is ideally higher than the energy of the T_1-state of the TADF emitter in order to prevent Dexter energy transfer of triplet excited states from the TADF emitter to the host material, which represents a major loss channel in TADF-based OLEDs.

Moreover, the HOMO- and LUMO-energy level differences between the host and emitter material need to be well adjusted. Large energy level differences between the host and emitter may cause direct charge trapping on the emitter or unwanted exciplex formation. The energy levels of the materials have to be carefully aligned in order to achieve the desired energy and/or charge carrier transfer between those two species, which helps in improving light-emitting performance.

Besides these two important points described above, a host for TADF should also have the following features [28, 43, 44]:

- **Thermal and morphological stability**: defined by the high glass transition temperature (T_g) for stabilizing the film morphology and inhibiting crystallization.

- **High material stability**: judged mainly by the bond dissociation energies (BDEs) of the single bonds of a molecule under three different conditions (cationic, anionic and neutral state).

- **Low polarity**: to reduce the emitter-host local dipole interactions that tend to shift the emission peak to longer wavelengths (bathochromic shift).

Furthermore, the triplet energy T_1 is sensitive towards the following [43, 45–48]:

- **Extended π-conjugation**: triplet energy decreases considerably in the line of benzene, biphenyl, and p-terphenyl. Also, fused ring systems lower the triplet energy (naphthalene less than biphenyl).

- **Connection pattern and torsion angles**: highly twisted molecular structures reduce the conjugation, increasing the triplet level; *meta*-linkage leads to a lower degree of conjugation and is more beneficial to get high triplet levels than *para*-linkage.

- **Aggregation**: bulky substituents weaken intermolecular reactions of π-conjugated host molecules, thus reducing the red-shift of phosphorescence spectra (T_1 increase). Hence, depending on the strength of interactions, T_1 measured in solution can be higher compared to those from neat films [49].

Stable hosts for blue TADF emitters are still very rare, because they require triplet energies above 3.0 eV to guarantee an efficient exciton confinement. Versatile building blocks like carbazole, thiophene, or benzofuran are often used for host and emitter materials targeted for deep blue, because of their high intrinsic triplet energies of 2.8–3.0 eV.

One of the most popular hosts for blue TADF is DPEPO, benefiting from the high triplet energy of 3.00 eV [50]. Unfortunately, OLED devices with DPEPO generally suffer from serious efficiency roll-off due to its poor stability [51]. Other conventional host examples classified by their potential charge transport characteristics are shown below [43, 52, 53] (**Figure 6**):
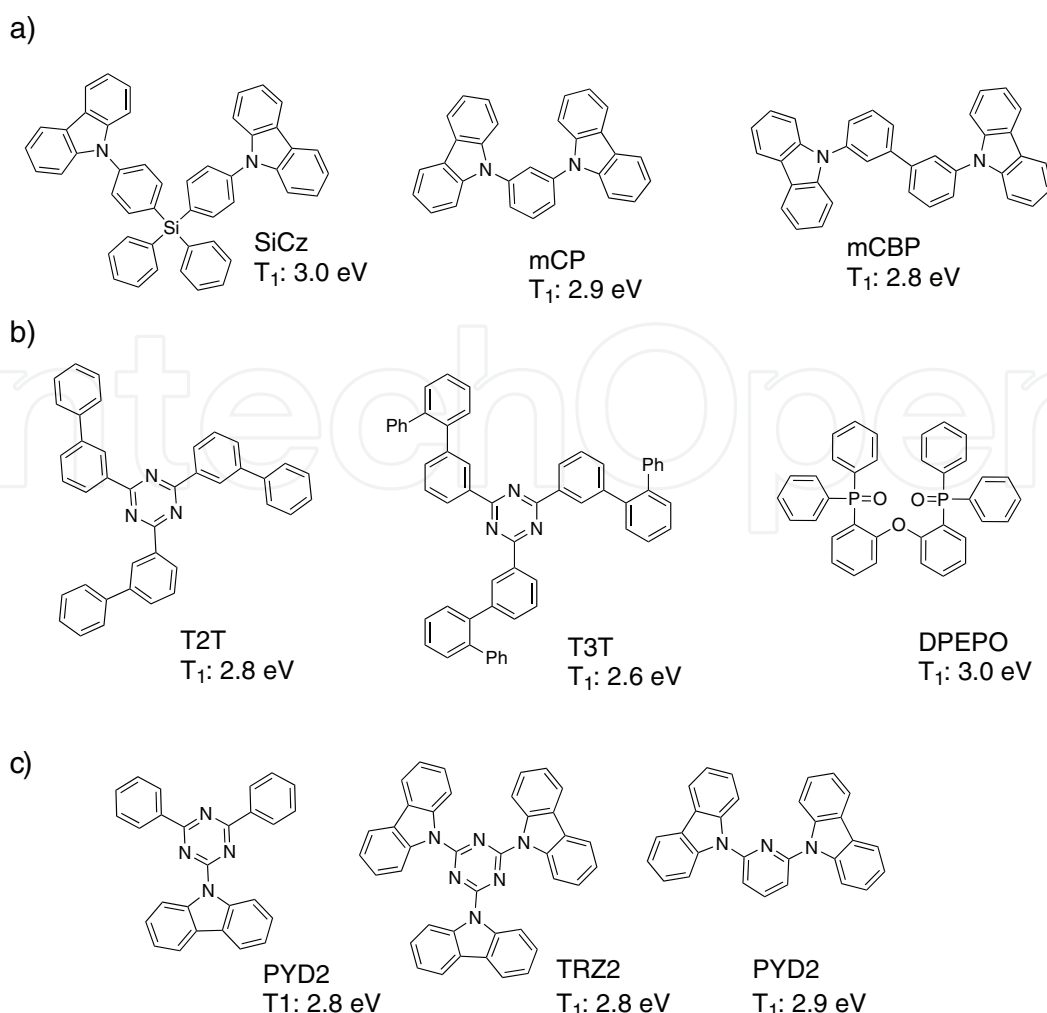
a)

SiCz
T1: 3.0 eV

mCP
T1: 2.9 eV

mCBP
T1: 2.8 eV

b)

T2T
T1: 2.8 eV

T3T
T1: 2.6 eV

DPEPO
T1: 3.0 eV

c)

PYD2
T1: 2.8 eV

TRZ2
T1: 2.8 eV

PYD2
T1: 2.9 eV

Figure 6.
Different host materials reported in the literature classified by their potential charge transport characteristics.
(a) p-type hosts (hole transport character). (b) n-type hosts (electron transport character). (c) Ambipolar
hosts (hole and electron transport character).

5. Next generation OLED: hyper-fluorescence

In the last few years, TADF emitters have become very popular for application in OLEDs, because of their triplet up-conversion property, which allows for high external quantum efficiency. In fact, TADF emitters can deliver device efficiencies, which can be up to three times higher than for OLEDs based on fluorescent dopants. However, many highly efficient TADF materials suffer from relatively strong degradation (e.g., due to long exciton lifetimes) and from broad emission spectra (characteristic for the intramolecular charge transfer states). One recently reported strategy to overcome those hurdles is the **hyper-fluorescence** approach (which is sometimes also referred to as TADF assisted fluorescence), first demonstrated by Adachi in 2014 [54].

In this approach, the outstanding properties of TADF molecules are utilized in combination with the narrow emission of fluorescent molecules: the TADF emitter serves as the triplet up-conversion material, which is responsible for high efficiency. After the up-conversion of triplet excited states to the singlet state of the TADF molecule, these singlet excited states can be transferred via Förster resonance energy transfer (FRET) to the S_1 state of the fluorescent emitter. Ideally, light emission occurs exclusively from the fluorescent dopant, which delivers a well-defined color point (**Figure 7**). If both, the rates of RISC and FRET are high, the overall excited state lifetime in this system is decreased, and hence the operational lifetime of the whole system is expected to be increased.

Hyper-fluorescence with all of its potential benefits is a very promising technology, which is not easy to engineer, because many criteria have to be met [54–58]. The two main criteria, which have to be fulfilled in order to achieve efficient hyper-fluorescence are an optimal spectral overlap of the TADF molecule's emission spectrum with the absorption spectrum of the fluorescent molecule and a high PLQY of both molecules. Achieving a great spectral overlap while maintaining a high device efficiency is especially challenging for hyper-fluorescence in the deep blue color range, where fluorescent materials with absorption peaks in the range of 400–450 nm and small Stokes shifts have to be combined with blue TADF emitters [57]. In addition, the TADF component should exhibit very fast reverse intersystem crossing from the triplet to the singlet excited state [57].

Moreover, the unwanted short-range Dexter energy transfer from the triplet state of the TADF emitter to the non-emitting triplet state of the fluorescent emitter should be avoided. Since Dexter transfer is highly dependent on the distance between the involved species, one way to minimize it is to physically separate the fluorescent and TADF emitting cores. This can be done by reducing the concentration of the fluorescent material in the system (typically ~1 wt.%) or by shielding the fluorescent dopant via the introduction of bulky side groups [55, 59]. This kind of molecular shielding is also beneficial to prevent self-quenching when using higher doping concentrations of the fluorescent material [60].

Finally, it is also important to align the HOMO and LUMO levels of all components within the emission layer (EML) in order to reduce charge trapping by the fluorescent material.

Besides using a conventional fluorescent molecule in such a "hyper-approach", where two emitters are combined, one can also use DABNA molecules, which were first introduced by Hatakeyama in 2016 [61]. DABNA derivatives are very interesting emitters for display applications in a hyper-approach, since they have even narrower emission and smaller Stokes shifts than most conventional fluorescent dopants.

Summarizing, hyper-fluorescence is a very complex approach where three or four materials are mixed within the EML and whose mechanisms are not yet fully understood. However, and despite the difficult and limited material selection, especially for the deep blue region, this technology is considered a promising
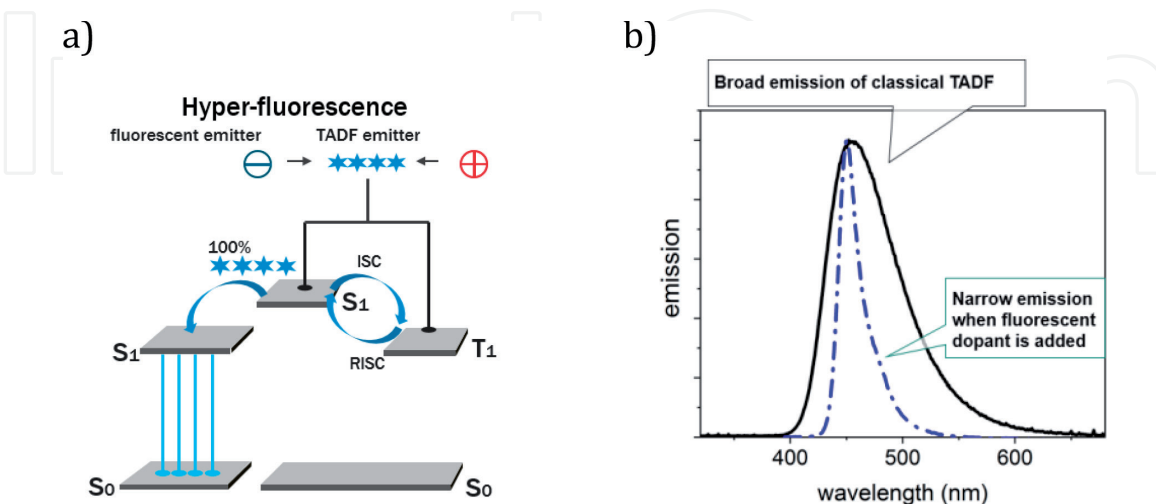

Figure 7.
(a) A simplified hyper-fluorescent diagram of a three-component system. The excitons are generated on the TADF material. The triplets are up-converted to singlets, which are further transferred via Förster resonance energy transfer (FRET) to the fluorescent dopant. The radiative decay to the ground state takes place on the fluorescent dopant. The host is omitted for clarity. (b) The FWHM of the emitting system based on TADF is significantly reduced when doped with a fluorescent material. Figure courtesy of CYNORA.

alternative for TADF and phosphorescence technologies, and holds the promise of high efficiency and stability as required by the display industry.

6. Industry status: Kyulux and CYNORA

Table 2 summarizes some of the device performances, which were published by CYNORA and one result announced by Kyulux. While the efficiency is usually reported at a similar brightness (1000 cd/m^2), comparing the results for color and device lifetime is not as easy, since color cannot be accurately defined by peak emission wavelength alone and device lifetime is often measured under different conditions depending on the preference of the company. A peak emission wavelength of ~460 nm is required for deep-blue OLED pixels, but this requirement is not sufficient to define the color. Additional parameters that also include the shape of the emission spectrum are the CIE 1931 coordinates CIEx and CIEy, which define a point in color space. For the deep blue region, it is usually sufficient to only look at the CIEy coordinate, which needs to be ≤0.15.

Device lifetimes are determined by measuring the decrease of luminance over time until a certain loss of the initial luminance is reached. If the luminance decay of a device was measured starting at a luminance of 750 cd/m^2 until the time were the luminance decreased by 5%, this lifetime value would be given as LT95 at 750 cd/m^2. Lifetimes measured under different conditions can be converted into other lifetime values. However, there is always an error connected to such a calculation. In general, it will always be the case that the lifetime is reduced for increasing brightness, and the lifetime is increased when a larger decrease in luminance is measured (LT90 is always longer than LT95).

In May 2017, CYNORA announced the result of a sky blue OLED with 15% EQE, a CIEy of 0.28, a peak emission of around 470 nm, and a LT95 at 750 cd/m^2 of around 190 hours. This was an important milestone on the way to an efficient deep blue TADF emitter. Before this result, TADF lifetimes LT95 for sky blue and deep blue had usually been in the minutes.

In December of the same year, CYNORA could build highly efficient OLED devices having 24% EQE with a deep blue TADF emitter at a CIEy of 0.15 and a peak emission of 460 nm. However, the device lifetime in this system was also reduced by roughly one order of magnitude to 30 hours. These two results impressively show the difficulty of reaching deep blue emission color together with high efficiency, and maintaining or improving device lifetime at the same time. These three factors,

	EQE at 1000 cd/m^2 (%)	CIEy	Peak emission (nm)	LT95 at 750 cd/m^2 (h)	Date
Deep-blue color requirement		≤0.15	~460		
CYNORA	15	0.28	<470	~190	May, 2017
	24	0.15	460	~30	Dec, 2017
	20	0.13	464	~15	August, 2018
Kyulux	22		470	~100	July, 2018 [62]

Table 2.
Status of Kyulux and CYNORA.

efficiency, color and lifetime, are clearly very closely linked, which means that device performance can only be compared between devices with the same color. Later in 2018, CYNORA also introduced results based on the hyper-approach. Even a lower CIEy of .013 at an emission wavelength of 464 nm together with a high EQE of 20% and a - for this color point- decent device lifetime of 15 hours LT95 at 750 cd/m^2 were achieved.

Also, in 2018 (July), Kyulux announced a first sky blue OLED device result based on a hyper-approach with an emission maximum at 470 nm, an EQE of 22% and an LT95 at 750 cd/m^2 of 100 hours.

Clearly, the results in the field of TADF of both companies, Kyulux and CYNORA, are impressive. Within just a few years, the companies showed that the TADF technology could be advanced from an interesting R&D topic to a serious contender for the next generation of high-efficiency emitters. The challenge for CYNORA is now to improve the stability of the TADF-based blue OLED pixel to a level that makes mass production with this technology feasible. A highly efficient and stable blue emitter will solve many technical issues for the display makers and pave the way for displays with lower power consumption and for higher display resolution.

7. Conclusion: what needs to be solved to get TADF ready?

From the latest improvements in academia and industry, it is clear that TADF technology is capable of achieving the desired blue color point necessary to succeed in the display field. Many TADF-based systems with deep blue color and high efficiency have been reported [9–11, 32]. However, challenges when going to deeper blue color remain the availability of suitable host materials with sufficiently high triplet levels and device stability. A way to circumvent the issue in the deep blue color region of having an emission onset at low wavelengths, that is, high energies, is to combine TADF emitters with narrow-emitting fluorescent dopants in the hyper-approach, where the excitons formed on the TADF material transfer their energy via FRET to the fluorescent emitter. Again, while this approach holds the promise of very narrow and efficient emission, engineering a three-component emissive layer requires the matching of several materials in terms of absorption and emission spectra as well as frontier molecular orbital alignment.

Finally, the most pressing issue and the one receiving the least attention in the literature remains the intrinsic stability of the materials, including the host, which is the material used at the highest concentration in the emissive layer, the TADF emitter, which determines the final efficiency of the device, and all stack materials which can potentially affect the device stability. From a molecular design point of view, chemically stable bonds are preferred. Moreover, in the device stack, the energy levels of all compounds need to be optimized in order to prevent too much stress on a particular material, which might lead to decomposition. This challenge is the focus of research-driven companies like CYNORA. After the fast development of the last years, we are confident that this advancement is achievable in a short period of time and that TADF technology will be ready for application soon.

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