Influence of the bias-dependent emission zone on exciton quenching and OLED efficiency

Markus Regnat, Kurt P. Pernstich, Beat Ruhstaller

Abstract

We present an electro-optical model of a three-layer phosphorescent OLED which accurately describes the measured current efficiency and transient electroluminescence decay for different biases. Central findings are a bias-dependent emission zone, which influences light outcoupling as well as exciton quenching, and the presence of strong triplet-polaron quenching even at low bias. The measured current efficiency initially increases up to 9 V before it decreases, where the increase is found to be caused by reduced triplet-polaron quenching with holes, while the decrease is caused by a reduced light outcoupling and increased triplet-triplet annihilation. The numerical model allows identifying the individual contributions of the exciton continuity equation and explains the electroluminescence decay, which deviates significantly from a mono-exponential decay due to the dominating influence of exciton generation and quenching after the external bias is removed.

1. Introduction

Over the last years OLED efficiencies increased up to nearly 40% due to the use of orientated phosphorescent [1–4] and TADF emitters [5–8] with internal quantum efficiencies close to 100%. Including different light scattering strategies for improved light outcoupling from the OLED stack, remarkable EQEs up to 62% were achieved [9–11]. Besides reaching high efficiencies, a major challenge for realizing OLEDs with high luminous intensities is still the efficiency roll-off at high biases due to exciton quenching processes, namely triplet-polaron quenching (TPQ) and/or triplet-triplet annihilation (TTA) [12,13].

To improve further the light emission at high biases, a better understanding of the underlying mechanisms, especially at high biases, is necessary. An important OLED characterization parameter is the current efficiency (CE) [14–16], which gives the ratio of the photometric measure luminance L to the applied current density j.

\[ \text{CE} = \frac{L}{j} \] (1)

In this study, we show that a bias-dependent position of the emission zone has an influence on the CE, as well as on the electroluminescence (EL) decay. Direct experimental evidence of a bias-dependent emission zone in the investigated OLED from optical measurements was presented by us recently [17]. In the work presented here, an elaborate electro-optical model is parametrized to describe quantitatively the measured current-voltage-luminance, the current efficiency, and the transient electroluminescence decay. This model also shows a strong bias dependence of the emission zone and further reveals that significant exciton quenching occurs already at low bias and that the strength of exciton quenching is influenced by the bias-dependent emission zone. Only with a combination of a bias-dependent emission zone - which influences the light outcoupling as well as exciton quenching - the observed trends in CE and EL decay can be explained.

Our study sheds light on the interplay between the position of the emission zone and exciton quenching, and highlights the importance of considering the details of the emission zone, particularly a possible bias dependence, when optimizing OLED efficiency.

2. Experimental

2.1. OLED fabrication

The investigated phosphorescent OLED stack (see inset to Fig. 1) consists of indium tin oxide ITO (100 nm)/PEDOT:PSS (30 nm)/TCTA (46 nm)/CBP:Ir(ppy)2(acac) (35 nm, 5 wt%)/NBPhen (52 nm)/Ca (15 nm)/Al (100 nm). The organic materials poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS), 4,4′,4″-tris(carbazol-...
9-y) triphenylamine (TCTA), 4,4′-bis(carbazol-9-y) biphenyl (CBP), bis
(2-phenylpyridine)(acetylacetonate)iridium(III) (Ir(ppy)$_2$(acac)) and
2,9-bis(naphthalen-2-yl)-4,7-diphenyl-1,10-phenanthroline (NBPhen)
were purchased from Heraeus Clevis™ and Lumtec. The glass sub-
strates with patterned ITO anode were purchased from Ossila Ltd. The
substrates were cleaned with acetone and isopropanol in an ultrasonic
bath and afterwards for 15 min with UV-ozone. A 30 nm thick PED-
OT:PSS film was spin coated in air and subsequently heated in a glo-
vebox for 40 min at 150 °C. All organic layers were deposited in high
vacuum (< 10$^{-6}$ mbar) by thermal sublimation. For the emission layer
Ir(ppy)$_2$(acac) and CBP were co-evaporated. Prior to the cathode de-
position, the shadow masks were exchanged under nitrogen atmosphere
to obtain a pixel area of 4.5 mm$^2$. After film deposition, the OLEDs were
encapsulated under nitrogen atmosphere.

2.2. Measurements

The electro-optical measurements were performed with the all-in-
one measurement system Paios and the characterization suite 4.12 from
Fluxim [18]. To measure the luminance a gated photomultiplier tube
(PMT H11526 Series) from Hamamatsu was employed and controlled
with Paios. The PMT output voltage $V_{PMT}$ is directly proportional to
the luminance because the electroluminescence (EL) spectrum is bias-in-
dependent, thus the PMT signal can be easily converted into luminance
with the luminous sensitivity of the PMT. The acceptance angle of the
PMT was $\approx \pm 10^\circ$ and the measured luminance is proportional to
the luminance at 0° to the surface normal (as obtained from the simula-
tions) because the angular emission spectrum is essentially independent
of the bias. To measure the J-V-L characteristics, voltage pulses with
magnitudes from 4 to 12 V were applied to the OLED while measuring
the current density $j$ and the luminance $L$. The length of the voltage
pulses was set to 200 $\mu$s in order to reach steady state, and the values for
$j$ and $L$ were averaged over the last 20 $\mu$s of each pulse. For the tran-
sient EL decay measurements the on-voltage was applied for 200 $\mu$s
before turning-off the OLED by applying 0 V. The JV characteristics
were also measured using a higher precision, stepwise voltage ramp with
longer integration time to obtain the $J$-$V$ curve over the entire bias
range.

2.3. Electro-optical model

Electro-optical simulations were carried out with a preview version
of Setfos 5.0 (Fluxim) [19]. Setfos calculates the position- and time-de-
and EQE has been reported before [35–37] and was explained by a non-
constant charge balance [34], which agrees with the findings presented
here. The decreasing CE at large bias can only be explained by con-
sidering exciton quenching as well as the bias-dependent change of the
emission zone, which leads to a reduced light outcoupling at high bias
as discussed next.

3.1. Influence of the emission zone on light outcoupling

In the electro-optical model, the luminance at 0° to the surface
normal is calculated from Ref. [38]:

\[ L = \frac{683 \text{ lm}}{W} \int y(\lambda) \cdot \frac{1}{2\pi} E_y(\lambda) \Lambda(\lambda) \int N_e(z) g(z, \lambda) dz d\lambda. \]

The value of 683 lm/W is the maximum of the luminous efficacy,
y(\lambda) is the dimensionless photopic luminosity function, E_y(\lambda) is the
photon energy, and \Lambda(\lambda) the intrinsic luminescence spectrum of the
emitting species. N_e(z) is the position-dependent number of photons
generated from the emitting dipoles, and g(z, \lambda) accounts for the op-
tical feedback of the OLED micro cavity on the emitting dipoles in-
cluding the effects of evanescent and guided modes, interference, light
trapping due to total internal reflection as well as absorption in the
individual layers [38].

To describe the influence of the bias-dependent emission zone on
light outcoupling, we introduce the light outcoupling factor \xi(z) shown in
Fig. 2, which quantifies the emitted luminance at 0° to the surface
normal as a function of emitter position. To obtain \xi(z), the luminance
was calculated as a function of the position z of a single emissive dipole
and normalized to its maximum value. The light outcoupling factor has
a maximum close to the EML/ETL interface. The maximum is slightly
shifted towards the hole transport layer (HTL) because the evaporated
electron transport layer (ETL) thickness was slightly lower (52 nm) than
the optimum value (56 nm) obtained from simulations performed prior
to device fabrication. At the HTL/EML interface, \xi(z) is reduced by
almost 50% due to a reduction of g(z).

In addition, Fig. 2 shows the spatial distribution of the generated
photons N_e(z) for different biases (dashed lines). At low biases, photons
are mainly generated at the EML/ETL interface, while for higher biases,
the maximum of the emission originates from the HTL/EML interface.
The solid lines in Fig. 2 represent the influence of the light outcoupling
on the generated photons. Integrating the effect of the position-depen-
dent light outcoupling factor and the bias-dependent distribution of

\[ \frac{dF(t, z)}{dt} = G \cdot R(t, z) + \nabla \cdot \left[ \frac{1}{2} F(z) \right] - k_{\text{rad}} \cdot F(t, z) - k_{\text{nondrad}} \cdot F(t, z) \]

\[ - n(t, z) - k_{\text{nondrad}} \cdot F(t, z)^2 \]

3.2. Influence of the emission zone on exciton quenching

As discussed above, the spatial distribution of emitting dipoles is
strongly bias-dependent, which also influences the exciton quenching
contributions at different biases. In the electro-optical model, the ex-
citon physics is modeled with the following exciton continuity equa-
tion:

\[ \frac{dN(z)}{dt} = \chi(\lambda) \int g(z, \lambda) dt - k_{\text{rad}} \cdot N(z) - k_{\text{nondrad}} \cdot N(z) \]

\[ - n(t, z) - k_{\text{nondrad}} \cdot N(z)^2 \]

\[ \frac{dF(t, z)}{dt} = G \cdot R(t, z) + \nabla \cdot \left[ \frac{1}{2} F(z) \right] - k_{\text{rad}} \cdot F(t, z) - k_{\text{nondrad}} \cdot F(t, z) \]

\[ - n(t, z) - k_{\text{nondrad}} \cdot F(t, z)^2 \]

\[ G \cdot R(t, z) \]

The integrated diode figure of merit is the maximum of the luminous ef-
ciciency of the emission zone on light outcoupling

\[ \int \xi(z) \cdot N_e(z) dz \]

3.1. Influence of the emission zone on light outcoupling

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\[ \frac{dF(t, z)}{dt} = G \cdot R(t, z) + \nabla \cdot \left[ \frac{1}{2} F(z) \right] - k_{\text{rad}} \cdot F(t, z) - k_{\text{ps}} \cdot F(t, z) \cdot p(t, z) - k_{\text{tr}} \cdot F(t, z) \]

\[ - n(t, z) - k_{\text{nondrad}} \cdot F(t, z)^2 \]

3.2. Influence of the emission zone on exciton quenching

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tion:

\[ \frac{dN(z)}{dt} = \chi(\lambda) \int g(z, \lambda) dt - k_{\text{rad}} \cdot N(z) - k_{\text{nondrad}} \cdot N(z) \]

\[ - n(t, z) - k_{\text{nondrad}} \cdot N(z)^2 \]
triplet-polaron quenching with holes (magenta line), followed by radiative recombination (green line). Triplet-triplet annihilation (cyan line) is strongly bias-dependent and becomes increasingly important at high bias. Non-radiative recombination (blue line) and triplet-polaron quenching with electrons (orange line) are only minor contributions to the exciton balance, which agrees with findings in Adachi et al. [23] and Oyama et al. [28]. The diffusion term in equation (3) vanishes after integration because exciton diffusion is limited to the EML.

Fig. 4a shows the relative contribution of the individual terms of the exciton continuity equation (eq. (3)) at each bias where 100% corresponds to the total number of generated excitons. The photons emitted into the hemisphere (red bars) are calculated via mode analysis from the radiatively decaying excitons \( \int F(t,z)k_{\text{rad}}(t,z)dz \). The light blue bars indicate the photons lost in evanescent, substrate and guided modes and through absorption. Fig. A1 shows these individual contributions. The shaded area in the light blue bars in Fig. 4a indicate the lost photons due to the light outcoupling losses described by \( \xi(z) \). As discussed in the context of Fig. 2, the position-dependent light outcoupling factor \( \xi(z) \) and the bias-dependent distribution of generated photons leads to a reduction of emitted photons by up to 25% for increasing biases. This corresponds to a loss of up to 8% of the generated excitons (shaded area in Fig. 4a). At low biases, the outcoupling losses due to EMZ change contribute with less than 1%.

Fig. 4b zooms into the region of out-coupled photons in Fig. 4a, and shows the percentage of photons emitted into an angular range of \( \pm 10^\circ \) (shaded bars) which increases up to 9 V before it decreases again at higher biases. The ratio of these out-coupled photons to generated excitons exactly resembles the measured current efficiency (cf. Fig. 4a) and generated excitons (\( \alpha_L \)).

The contributions of non-radiative recombination (blue bars in Fig. 4a) and triplet-polaron quenching with electrons (orange bars in Fig. 4a) are essentially bias-independent and contribute with 1–2% and 1–3% to the total losses of generated excitons. Triplet-triplet annihilation (cyan bars in Fig. 4a) becomes significant at high bias due to the quadratic dependence on exciton density and contributes up to 19% to the total losses. As can be seen from the magenta bars in Fig. 4, triplet-polaron quenching with holes is the largest loss mechanism. Interestingly, the TPQh losses at low bias are rather large and decrease at higher bias. The behavior of TPQ with holes is explained in Fig. 5, which shows the exciton distribution together with the electron and hole densities for 5 and 11.5 V.

At 5 V (Fig. 5a) the majority of electrons are in the ETL, while the holes accumulate at the EML side of the EML/ETL interface. Thus, the exciton density has a maximum at this interface and TPQ with holes is prominent. At 11.5 V (Fig. 5b), a significant amount of electrons is being injected into the EML. Due to the larger field-dependence of the mobility for electrons than for holes, the effective electron mobility is larger than the hole mobility (cf. insets to Fig. 5), electrons accumulate at the HTL/EML interface. The main exciton density is now at the HTL/EML interface where the hole density is low, and TPQ with holes becomes less prominent at high biases. We like to note that the large field dependent electron mobility is required to explain the shift of the EMZ with bias as presented previously [17].

In References [39,40], two similar OLED stacks with larger EQE and similar emission zone have been presented. In those OLEDs, no energy barrier for electrons was present at the EML/ETL interface. When zeroing this energy barrier in our model, an increased electron density in the EML close to the EML/ETL interface is obtained. These electrons recombine, thereby reducing the number of excessive holes present at the EML/ETL interface. This significantly reduces the contribution of TPQ to 9% and increases the EQE to 13%. The EQE is, thus, strongly influenced by this energy barrier.

From the insights gained from the electro-optical model, the measured current efficiency (cf. Figs. 1 and 4a and b) can be well understood: the initial CE increase is due to a reduction of TPQ with holes because the emission zone shifts away from regions with large hole density. The decrease of CE at high bias is caused by increased TTA losses and by increased outcoupling losses due to the shifting emission zone. Thus, both CE trends, the increase and the decrease, are linked to the bias-dependent emission zone.

3.3. Influence of the emission zone on the EL decay

The decay time of emissive dipoles is known to depend on the local optical environment, and can be described by considering the position-dependent Purcell factor \( F(z) \). The Purcell effect describes the dynamics of the dipole emission within an optical cavity, and a lower Purcell factor leads to a reduced spontaneous emission rate, and, thus, to a longer decay time [20]. Because the emission zone in the investigated OLED stack shifts with bias, the electroluminescence decay rate is expected to change due to the Purcell effect. Fig. 6 shows the position-dependent Purcell factor together with the radiative exciton density rate calculated with the true Purcell factor (solid lines) and with a fictitious, constant Purcell factor of 1.65 (dashed lines). At low bias, the main emission originates at the EML/ETL interface with \( F \) being 1.65, while for high biases, the emission zone shifts towards the HTL/EML interface where \( F \) is reduced to 1.2.

The shaded area in Fig. 6 indicates the reduction of the radiative exciton decay rate due to the changes of the emission zone and the accompanying reduced Purcell effect. With increasing bias, the contribution of the Purcell effect monotonically increases, which leads to an increased decay time (see equation (4) below). The measured decay time in the inset to Fig. 7 reveals a bias region with increasing decay

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**Fig. 4.** Relative contributions of the individual terms of the exciton continuity equation where 100% corresponds to the total number of generated excitons (a) and the comparison of the outcoupled photons to the measured and simulated current efficiency (b). See text for details.
time, but also a bias region with decreasing decay time, thus the contributions from the Purcell effect alone cannot explain the measurements.

As discussed in the previous section, exciton quenching plays a dominant role in explaining the measured trend in current efficiency. Exciton quenching is also known to influence the radiative decay time $\tau$ in electroluminescence and in photoluminescence (PL) experiments. In the absence of exciton quenching, a mono-exponential decay of the PL signal is expected after the laser excitation is turned-off, because only the terms describing radiative and non-radiative decay remain in the exciton continuity equation (cf. equation (3)). In such a case, the PL decay time $\tau_{PL}$ is directly related to the (non-)radiative decay rates $\tau_{rad}^{\text{nonrad}}$(4)

$$\tau_{rad}^{\text{nonrad}} = \frac{1}{F k_{rad} + k_{nonrad}}$$

When the PL decay is measured while a bias is applied to the OLED, the electron and hole densities in equation (3) remain constant, thus allowing to elucidate the rates for TPQ with holes and electrons [28,34]. By varying the intensity of the exciting light, information about TTA can be obtained [41]. All PL experiments have in common that the exciton generation term vanishes immediately after the excitation source is switched off.

In contrast, the EL decay is fundamentally different, because the generation term in equation (3) can persist over long times, in our case a few microseconds. The generation term strongly depends on the applied bias before turn-off, and is influenced by a multitude of variables, foremost the charge carrier distribution, the electric field inside the EML and the charge carrier mobilities as discussed in the context of Fig. 8.

Fig. 7 shows the measured and simulated EL decay for different on-voltages. The inset shows the initial EL decay times extracted from the measured (symbols) and simulated (solid line) EL signal.
intrinsic (non)-radiative decay rates from equation (4), if the intrinsic quantum efficiency (\(\eta_{\text{intrinsic}} = \frac{\kappa_{\text{rad}}}{\kappa_{\text{rad}} + \kappa_{\text{nonrad}}} = 0.889\)) and the Purcell factor are known. Using the Purcell factor where the exciton density at 5 V is largest (\(F_{\text{EML/ETL}} = 1.65\)), the values \(\kappa_{\text{rad}} = 0.64 \, \mu s^{-1}\) and \(\kappa_{\text{nonrad}} = 0.08 \, \mu s^{-1}\) were calculated, which agrees well with the values of 0.613 \(\mu s^{-1}\) and 0.077 \(\mu s^{-1}\) used in the simulations. With these rate constants, an intrinsic emitter lifetime of \(\tau_{\text{intrinsic}} = \frac{1}{\kappa_{\text{rad}} + \kappa_{\text{nonrad}}} = 1.39 \, \mu s\) was calculated, which is close to the value of 1.6 \(\mu s\) measured in PL experiments in solution [42]. Thus, in the special case where certain terms in the exciton continuity equation cancel each other so that only the radiative and non-radiative terms remain, the mono-exponential EL decay can be used to extract the intrinsic emitter lifetime.

At intermediate biases (Fig. 8b and c), the generation term shows a sudden drop and the TPQh term is dominating the EL decay for \(\approx 0.25 \, \mu s\) before the generation term starts to dominate the decay. At high bias (Fig. 8d), the TTA term (\(\int k_{\text{rad}} \cdot R^2 \, dr\)) becomes significant up to \(\approx 0.25 \, \mu s\), after which it vanishes quickly. The generation term at this bias is also negligible and the EL decay is dominated only by TPQ with holes.

We like to note, that the individual contributions shown in Fig. 8 strongly depend on the OLED stack and, therefore, cannot easily be generalized. Nevertheless, Fig. 8 highlights that, in general, a full electro-optical model is required to extract the exciton rate constants and the intrinsic emitter lifetime from EL decay measurements.

### 4. Conclusion

We measured the current density - voltage - luminance (J-V-L), current efficiency (CE) and transient EL characteristics of a phosphorescent OLED. The current efficiency showed an unexpected increase up to 9 V followed by a decrease. An electro-optical model was devised to describe all measurements simultaneously. The model enabled insights into the mechanisms leading to the observed CE trends. A central outcome was that the emission zone changes with bias, which has manifold consequences. The bias-dependent emission zone causes an increase of the light outcoupling losses due to a reduced light outcoupling factor at high bias. Additionally, this shift of the emission zone significantly reduces the contribution of the triplet-polaron quenching at high bias, because the main emission occurs in a region with lower hole density. Only the combination of the reduced TPQ contribution with the increased light outcoupling losses and TTA contribution could explain the measured CE.

The model further allowed identifying individual contributions from the exciton continuity equation. Because of the dominating role of the exciton generation term, the EL decay is in general not mono-exponential, and the initial decay time is related to the intrinsic emitter lifetime only under special circumstances when the generation term is cancelled by the TPQ term.

This work highlights the benefits of an accurate knowledge of the emission zone and exciton quenching to reveal the details of the mechanism leading to the efficiency roll-off at high biases. An electro-optical model is, thus, a useful tool to identify strategies to further improve OLED efficiency.

### Acknowledgements

We thank, S. Jenatsch, B. Blüelle, S. Züfel, A. Stous and A. Gentsch from Fluxim AG and F. Nüesch from EPFL for fruitful discussions and valuable comments. Financial support from the Swiss National Science Foundation under grant no. 162230 is gratefully appreciated.

### Appendix

#### Table 1

Optimized model parameters used in the electro-optical simulations.

<table>
<thead>
<tr>
<th>Optimized Parameters</th>
<th>Optimized Values</th>
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<tbody>
<tr>
<td><strong>PEDOT-PSS</strong></td>
<td></td>
</tr>
<tr>
<td>Work function (eV)</td>
<td>5.14</td>
</tr>
<tr>
<td>Thickness (nm)</td>
<td>30</td>
</tr>
<tr>
<td>TCTA</td>
<td></td>
</tr>
<tr>
<td>LUMO (eV)</td>
<td>2.3</td>
</tr>
<tr>
<td>HOMO (eV)</td>
<td>5.65</td>
</tr>
<tr>
<td>(^1)Mobility (\mu_h) (m(^2)/Vs)</td>
<td>(3.3e-14, \gamma = 0.9e-3^*)</td>
</tr>
<tr>
<td>(^3)Mobility (\mu_h) (m(^2)/Vs)</td>
<td>(1.8e-7, \gamma = 7.1e-7)</td>
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<tr>
<td>Thickness (nm)</td>
<td>46</td>
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<tr>
<td><strong>CBP</strong></td>
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<tr>
<td>LUMO (eV)</td>
<td>2.56</td>
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<tr>
<td>HOMO (eV)</td>
<td>5.71</td>
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<tr>
<td>(^1)Mobility (\mu_h) (m(^2)/Vs)</td>
<td>(3.1e-16, \gamma = 1.4e-3)</td>
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<tr>
<td>(^3)Mobility (\mu_h) (m(^2)/Vs)</td>
<td>(6.0e-11, \gamma = 4.5e-9)</td>
</tr>
<tr>
<td>Thickness (nm)</td>
<td>35</td>
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<tr>
<td><strong>NBPhen</strong></td>
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Fig. 8. Integrated exciton rates for generation (black lines), triplet-polaron quenching with holes (blue lines) and triplet-triplet annihilation (green line) to illustrate the respective contribution on the EL decay (red lines) at different biases.
Table 1 (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>LUMO (eV)</td>
<td>2.8</td>
</tr>
<tr>
<td>HOMO (eV)</td>
<td>6.4</td>
</tr>
</tbody>
</table>

†Mobility \( \mu_{t} \) (m\(^2\)/Vs) \( \mu_{t} = 5.0 \times 10^{-8}, \gamma = 1.5 \times 10^{-4} \)

‡Mobility \( \mu_{p} \) (m\(^2\)/Vs) \( \mu_{p} = 1.0 \times 10^{-12}, \gamma = 1.0 \times 10^{-8} \)

<table>
<thead>
<tr>
<th>Thickness (nm)</th>
<th>52</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
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</table>

| Work function (V) | 2.93 |
| Thickness (nm)    | 15   |

**Excitonic Parameters in CBP**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Exciton formation ratio ( G(1) )</td>
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</tr>
<tr>
<td>Diffusion constant ( \text{cm}^2/\mu\text{s} )</td>
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</tr>
<tr>
<td>Radiative rate ( k_{rad} ) (( \mu\text{s}^{-1} ))</td>
<td>0.61</td>
</tr>
<tr>
<td>Non-radiative rate ( k_{nonrad} ) (( \mu\text{s}^{-1} ))</td>
<td>0.08</td>
</tr>
<tr>
<td>Annihilation rate ( k_{ann} ) (cm(^3)/s)</td>
<td>3.6e-12</td>
</tr>
<tr>
<td>TPQ- rate ( k_{TPQ-} ) (cm(^3)/s)</td>
<td>9.5e-12</td>
</tr>
<tr>
<td>TPQ+ rate ( k_{TPQ+} ) (cm(^3)/s)</td>
<td>3.6e-12</td>
</tr>
</tbody>
</table>

**Dipole orientation (1)** 0.24

**Electric parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Series resistance ( R_s ) (Ohm)</td>
<td>10</td>
</tr>
<tr>
<td>Parallel resistance ( R_p ) (MOhm)</td>
<td>15</td>
</tr>
</tbody>
</table>

† fixed model parameters.

‡ \( \mu = \mu_{t} e^{-E/\gamma} \) with \( \mu_{t} \) zero field mobility, \( \gamma \) field coefficient and \( E \) electric field, *the large field-coefficient is a result of the optimization and could also be chosen much smaller without influencing the results.*

Fig. A1. Relative contributions of photons emitted into air and dissipated in the OLED stack where 100% corresponds to the total number of generated excitons (cf. Fig. 4).

References


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