# Research Performance Final Report

**Project Title:** Combining Fluorescence and Phosphorescence to Achieve Very Long Lifetime and Efficient White OLEDs

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## Project Objectives

Our proposed approach uses a combination of a blue fluorescent (fl) emitter and green/red phosphorescent (ph) emitters to cover the visible spectrum, resulting in a high efficiency, white emission. Specifically, we will strive to achieve the following:

- Develop fl, ph, host and transport materials that lead to very high quantum (EQE > 25%) and power efficiencies (> 50 lm/W without substantial outcoupling enhancement).
- Lifetime studies will be carried out at each step of the process, with an objective to lifetime by the end of our two year program of $L_{70}$ > 25,000 hrs for a WOLED with a CRI > 90 at an initial brightness of 5,000 lm/m$^2$.

These objectives will be achieved by multiple parallel tracks of research. In the first research track we will prepare emissive dopants that fluoresce strongly in the blue and have a small energy gap (< 0.4 eV) between their singlet and triplet states. This small $S_1/T_1$ gap will prevent triplet excitons from being trapped at the fluorescent dopant.

In the second research track, we will prepare and test two different types of host material for hybrid fl/ph WOLEDs. The first type will have a large $S_1/T_1$ energy gaps, such that the energies of the fluorescent dopants are nested within the host, *i.e.* the $S_1$ and $T_1$ energies are less than the $S_1$ energy of the host and greater than the $T_1$ energy of the host. In this way singlets will be trapped at the fl-dopant and triplets will localized on the host to be transported to the phosphorescent dopant. A second type of host matrix will be investigated as well, in which the host matrix fluoresces strongly in the blue and has a triplet energy in the green, sufficiently high to transfer triplet excitons to a phosphorescent dopant. A good example of such a host material is 4PNPD, introduced by Leo, *et. al.* While this material is promising the triplet energy is lower than we would like for a hybrid WOLED.

In parallel with the development of new materials for fl/ph WOLEDs we are preparing and life testing both known materials systems (for benchmarking) and new materials in the Forrest lab as they are available from the Thompson lab.

**Accomplishments in this program:**

### Summary

The objective of our project was to develop a high efficiency, long lived WOLED using a hybrid approach to harvesting singlet and triplet excitons, as described above. WE met out GONOGO metric at the end of year one, achieving an efficiency of nearly 50 lm/W for high quality white light emission. We faced an unforeseen problem in achieving this high efficiency level at high brightness. Our hybrid devices showed a significant roll off in device efficiency as the current is raised, such that our efficiency dropped to *ca.* 10 lm/W at 1000 nits. This roll off precluded us form achieving our send year targets with regards to efficiency at high brightness and long device lifetime. We spent the majority of our efforts in year two trying to decrease or eliminate this efficiency roll off, but this roll off prevented us from reaching our end of program target of high efficiency at high brightness with long device lifetime. Toward the end of the sixth quarter of the program we began to investigate a new approach, which involved a tandem WOLED, with a hybrid blue/red OLED stacked on a phosphorescent green OLED. The resultant emission from the stack will be white and the tandem structure relaxes the constraints on the materials, which we believe is key issue in the high roll off in efficiency. We continue to work on this approach, under support from the Universal Display Corporation and are seeing great promise in this tandem approach.

*Program Accomplishments*

The best way to review the accomplishments we have achieved over the last two years is to review each of the milestones. We generated a comprehensive set of milestones for this project and they outline our progress toward our goals very well. Our project was broken down to four tasks, listed below. While these takes appear sequential, they are in fact all run in parallel. Some of the milestones required the discovery and synthesis of ne materials at USC to be transferred to UM for device work. That process did gate the progress toward some of the milestones, but the UM team had ample work to do in modeling devices with known materials while the USC team proceeded through the materials discovery process. The milestone numbers are tied to the task they relate to.

Task 1, Develop fluorescent blue dopants: The fl dopants in our WOLEDs will give blue fluorescence ($\lambda_{max} \leq 470$ nm) with high efficiency ($\Phi_{PL} > 70\%$), and a small singlet-triplet energy gap ($\Delta E_{ST} < 0.4$ eV).

Task 2, New host materials for hybrid fl/ph WOLEDs: Single carrier materials will confine carrier recombination to a single interface. Hosts with large $S_1$-$T_1$ gaps will accept fl dopant triplets.

Task 3, Development of hybrid fl/ph WOLEDs: fl and ph dopants developed in 1 and 2 will be folded into optimal WOLED structures to achieve high brightness and efficiency (> 50 lm/W).

Task 4, Device lifetime measurements: fl OLEDs and WOLEDs will be life-tested under accelerated aging conditions

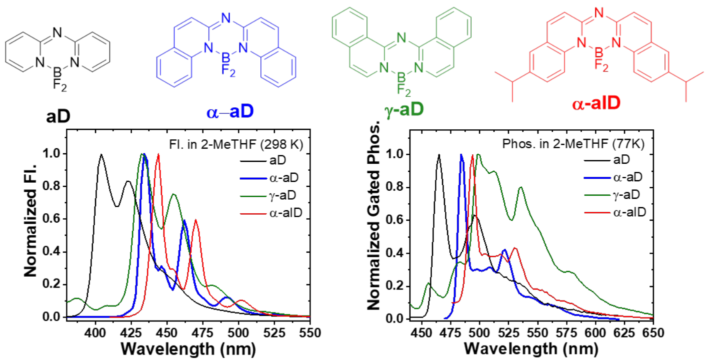
*Year 1 Milestones*

Milestone 1.1 (Projected M3, completed M3): Computer model >3000 blue fl dopants for $S_1$, $T_1$, HOMO and LUMO energies. This process led to the discovery of the aza-DIPYR family of fluorescent dopants. Hs family of materials were predicted to give deep blue fluorescence with $\Delta E_{ST} < 0.4$ eV.

Milestone 1.2.1 (Projected M6, completed M6): Prepare two fl dopants and carryout photophysical studies.

Milestone 1.2.2 (Projected M9, completed M9)*:* Prepare four fl dopants and carryout photophysical studies.

We prepared far more than six fluorescent dopants, all of which gave high fluorescence efficiency and $\Delta E_{ST} < 0.3$ eV. Figure 1.2.2 below shows four of these emitters. The three blue emitters have $\Phi_{PL} > 0.85$. This family of fluorescent dopants was carried forward into Task 3.



| Exp. results | aD | α-aD | γ-aD | α-aID |
|---|---|---|---|---|
| $S_1$ (eV) | 3.11<br>(398 nm) | 2.86<br>(434 nm) | 2.87<br>(432 nm) | 2.79<br>(444 nm) |
| $T_1$ (eV) | 2.65<br>(467 nm) | 2.56<br>(484 nm) | 2.57<br>(482 nm) | 2.51<br>(494 nm) |
| **$\Delta(S_1/T_1)$** | **0.39** | **0.30** | **0.30** | **0.28** |
| Solution $\Phi_{PL}$ | 0.42 | 0.86 | 0.87 | 0.87 |
| PMMA $\Phi_{PL}$ | 0.48 | 0.86 | 0.90 | 0.87 |

Figure 1.2.2: Four fluorescent dopants prepared in this program. The blue emitting materials all give high fluorescent efficiency and $\Delta E_{ST} \leq 0.3$ eV.

Milestone 1.3 (Projected M12, completed M9): Prepare blue fluorescent OLED with fl dopants using conventional fluorescent blue OLED host materials with EQE $\geq$ 4% (without outcoupling enhancement).

We prepared blue fluorescent OLEDs with α-aD and achieved an external efficiency (EQE) of 4.5 % (see Figure 1.3). This high EQE value was only obtained at a doping level of 1%. At higher doping levels self-absorption of the emission by the dopant decreased the EQE and changed the line shape by diminishing the highest energy feature in the luminance spectra.

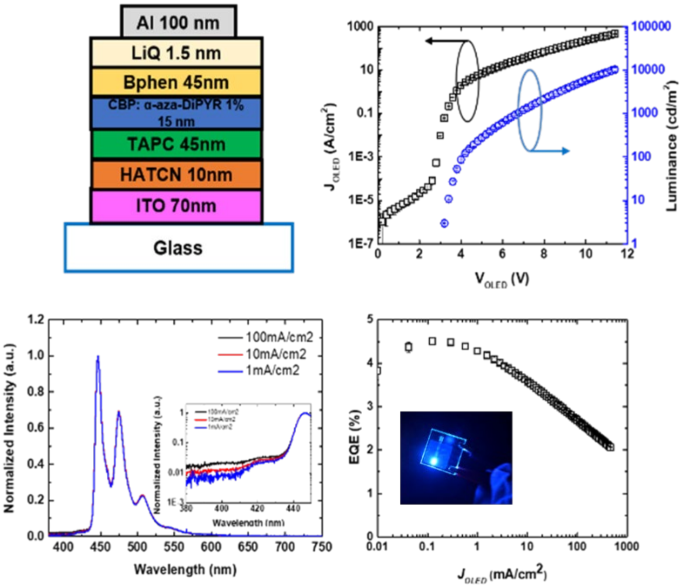


Figure 1.3: Blue fluorescent OLEDs prepard with α-aD in a CBP host matrix.

Milestone 2.1 (Projected M6, Completed M6): Computationally model 100 hole and electron transporting host materials for $S_1$, $T_1$, HOMO and LUMO energies.

We modeled > 300 potential host materials, estimating the $S_1$, $T_1$, HOMO, LUMO and reorganization energies.

Milestone 2.2.1 (Projected M12, Completed M9): Prepare hole transporting host materials for dopants of Task 1.4.

We set out to study indolocarbazoles and related hole transporting host materials. They all had the right $S_1$, $T_1$, HOMO and LUMO energies to make them good host candidates for hybrid devices. They were synthesized, purified and studied in OLEDs. We chose the fluorescent DIPYR dopants prepared in task one to study in these host lattices. Unfortunately, the OLED efficiency was very low. The dopants of task one have deep HOMO and LUMO levels and the doped film gives weak exciplex emission. We substituted the indocarbazoles with pyridyl and pyrimidinyl groups in an attempt the prepare hosts with deeper HOMO energies, but only exciplex emission is observed. We shifted our attention to electron transporting host materials and developed them ahead of out initial schedule. See Task 2.2.2 below.

Milestone 3.1 (Projected M9, Completed M9): Demonstrate hybrid fl/ph WOLEDs incorporating fl dopant from this program (Task 1.3) in a conventional fl/ph WOLED host (CBP) with phosphorescent green [$Ir(ppy)_3$] and red (PQIr) dopants, giving efficiency > 30 lm/W at 10,000 lm/m$^2$ and CRI > 80.

This milestone was completed, but the efficiency target of the milestone was not met. The milestone is based on a specific set of host and phosphorescent dopant materials, which limited our efficiency to < 20 lm/W. The low efficiency was improved int eh subsequent milestone.

Milestone 3.2 (Projected M12, Completed M21): Demonstrate hybrid fl/ph WOLEDs incorporating fl dopant and host from this program with phosphorescent green and red dopants, giving efficiency > 40 lm/W at 10,000 lm/m$^2$ and CRI > 80.

This milestone was completed, but the efficiency target of the milestone was not met at a brightness of 10,000 lm/m$^2$. Our WOLEDs suffered from substantial roll-off in device efficiency at high brightness. The completion of the Milestone was delayed while we attempted to eliminate or decrease the roll off problem. We completed the program with this roll off issue at the center of our research.

Milestone 4.1 (Projected M6, Completed M6): Test lifetime of published fl/ph WOLED for benchmarking.

Milestone 4.2 (Projected M9, Completed M15): Test lifetime of fl-blue OLEDs of Task 1.3.

The delay in completing this milestone was due to a breakdown of the lifetime testing system. It was down for close to five months while the problems were troubleshot.

Milestone 4.3.1 (Projected M12, M21 80% Completed): Test lifetime of fl-blue OLED of Task 1.4.1. Demonstrate lifetime ($L_{70}$) > 25,000 hours at an initial luminance of 3,000 lm/m$^2$.

The lifetime testing system delayed the completion of Milestone 4.2. The lifetime testing was completed, but the lifetime target was not met. We believe that this is due to the need for a more stable hole blocking material.

Go/No-Go Decision Point Summary (End of Year 1, Completed M12): Demonstrate a hybrid fl/ph WOLED achieving luminance efficiency > 40 lm/W and a CRI > 80.

We reached our target by optimizing the device structure using a CBP:Ir(ppy)3 green extraction layer and **I5** as a host for phosphorescent red emission as well as fluorescent blue emission. Previously, BPhen was used as an electron transport layer but we have discovered that the device efficiency is improved when we substitute BPhen with TPBi. Optical outcoupling calculations were performed to optimize transport layer thicknesses based on the emission position of each color within the device. Calculations, summarized in **figure GNGa**, were performed assuming red emission from the center of the **I5** layer, green and blue emission from CBP/**I5** interface. Based on these results we chose an ETL thickness of 40nm and HTL thickness of 60nm. The optimized device structure and its performance is displayed in **figure GNGb**.

The optimized I5 host device shows high conductivity, reaching 100mA/cm2 at 10.3V and peak external quantum efficiency of 20%. Overall, the device luminous power efficacy peaks at 47.4lm/W at turn on. The device is dominated by red emission at low current, having a low CRI of 78.4 with CIE coordinates (0.52,0.4) but is improved at higher currents to 93.6 CRI at CIE coordinates of (0.38,0.39). This device has met our Go/No-go requirement.

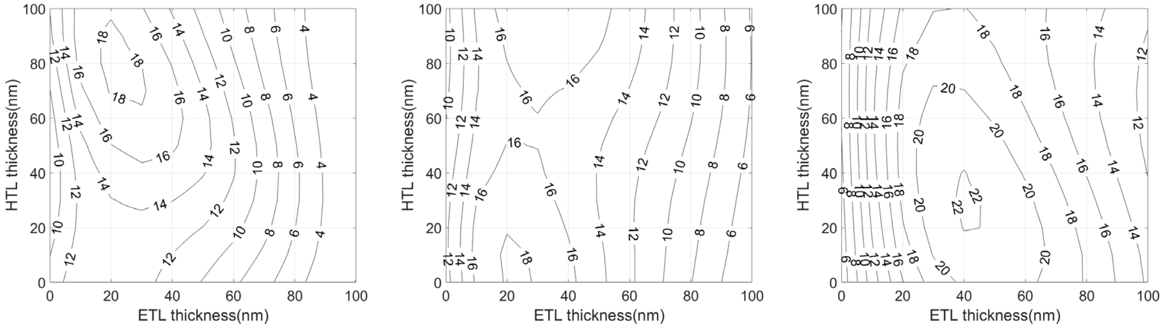


**Figure GNGa**: Outcoupling calculations for optimizing I5 white device. Calculations for blue, green, red from left to right.

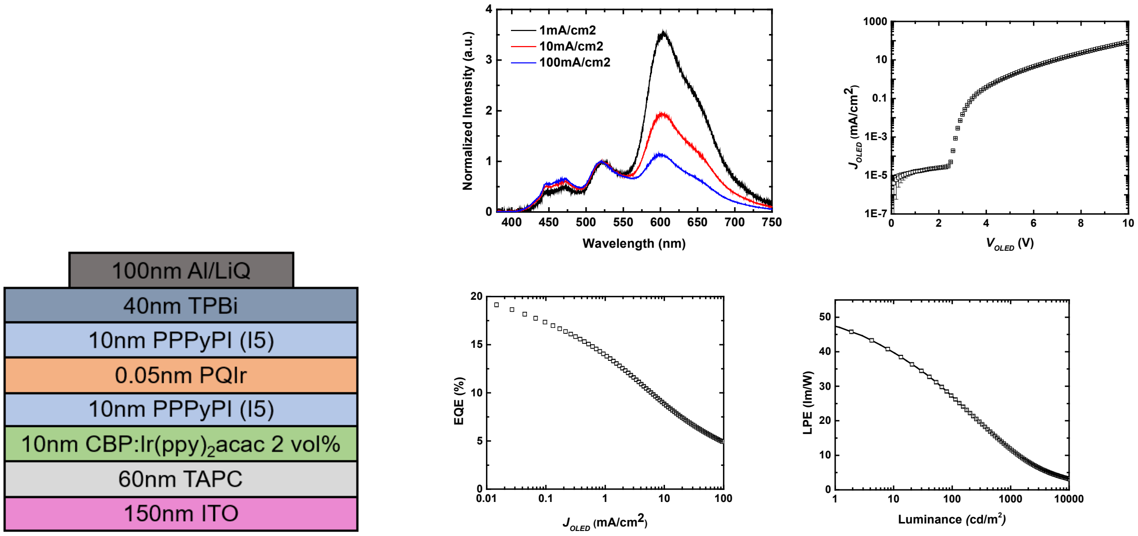


**Figure GNGb**: Optimized I5 host device with green extraction layer.

## Year 2 Milestones

Milestone 1.4.1 (Projected M18, Completed M18): Prepare blue fluorescent OLED with dopants of Task 1.3 with using hole transporting hosts of Task 2 with EQE ≥ 5% (no outcoupling enhancement).

As described above, the new hole conducting host matrices we prepared as part of this program quenched the emission from α-aD. We did however prepare hot materials that emitted as neat materials that were used to meet this milestone. The efficiency of this device met our target.

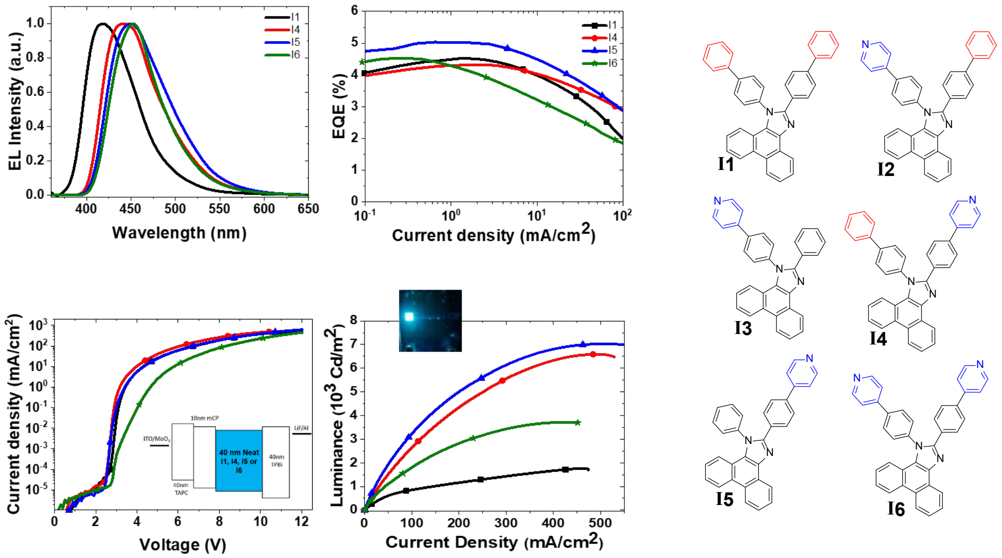


**Figure 1.4.1:** Blue fluorescent OLEDs with neat host emitters. Device data are shown for OLEDs based on I1, I4, I5 and I6.

Milestone 1.4.2 (Projected M21, 80% completed M21): Prepare blue fluorescent OLED with dopants of Task 1.3 with using electron transporting hosts of Task 2 with EQE ≥ 5% (no outcoupling enhancement).

OLEDs were prepared with α-aD doped into I4, I5 and I6. We did not reach an efficiency of 5%, but further optimization would have pushed us there. We felt that it was better to use this material and move on to white OLEDs than to spend time on this optimization. The data for these OLEDs is shown below.

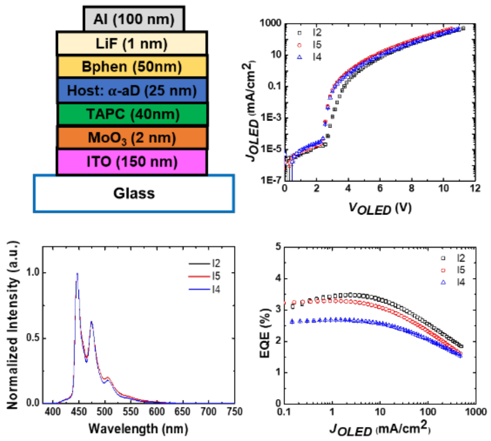


**Figure 1.4.2:** OLED data for α-aD doped OLEDs Host identities are given in the previous figure.

Milestone 2.2.2 (Projected M15, Completed M15): Prepare electron transporting host materials for dopants of Task 1.4.

The host materials illustrated in **Figure 1.4.1** (I1-I6) were prepared and thoroughly characterized.

| | $S_1$ (Soln) | $S_1$ (Solid) | $T_1$ (Soln) | $T_1$ (Solid) | PLQY (%) soln | PLQY (%) neat film |
|---|---|---|---|---|---|---|
| I1 | 373 | 377 | 441 | 468 | 99 | 95 |
| I2 | 375 | 382 | 477 | 490 | 28 | - |
| I3 | 365 | 370 | 460 | 478 | 28 | - |
| I4 | 390 | 412 | 478 | 520 | 99 | 55 |
| I5 | 390 | 406 | 480 | 520 | 99 | 81 |
| I6 | 386 | 410 | 475 | 495 | 99 | 83 |
| 4P-NPD | 380 | 415 | - | 525 | 69 | 57 |
| CBP | 347 | 378 | 440 | 465 | - | - |

Milestone 3.3 (Projected M21, Completed M24): Demonstrate fl/ph WOLEDs with fl dopant and host from Tasks 2.4, 2.5 with optimized ph dopants, giving efficiency >45 lm/W and CRI >90 at 10,000 lm/m$^2$.

The milestone was focused on the demonstration of device hybrid WOLEDs with materials from this program. We prepared hybrid WOLEDs with a range of different architectures and materials sets, and met the efficiency target, but not at the prescribed brightness. The devices suffered from substantial efficiency roll off at high brightness. Using singlet and triplet sensors we determined that the efficiency roll off was due to both charge trapping at the ph-dopant and TTA/TPA at the EML/HTL interface. We made a number of attempts to decrease the roll off in device efficiency. One promising route is to use a mixed host, which distributes the recombination, away from the interface. This is illustrated in the device shown in **Figure 3.3a**. The EML here is a 50:50 mixture of CBP and the blue fluorescent host I5 (PPPyPI). This gives both enhanced efficiency and decreased roll off.

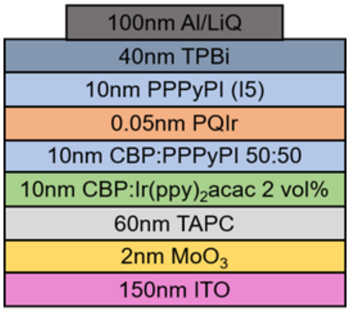
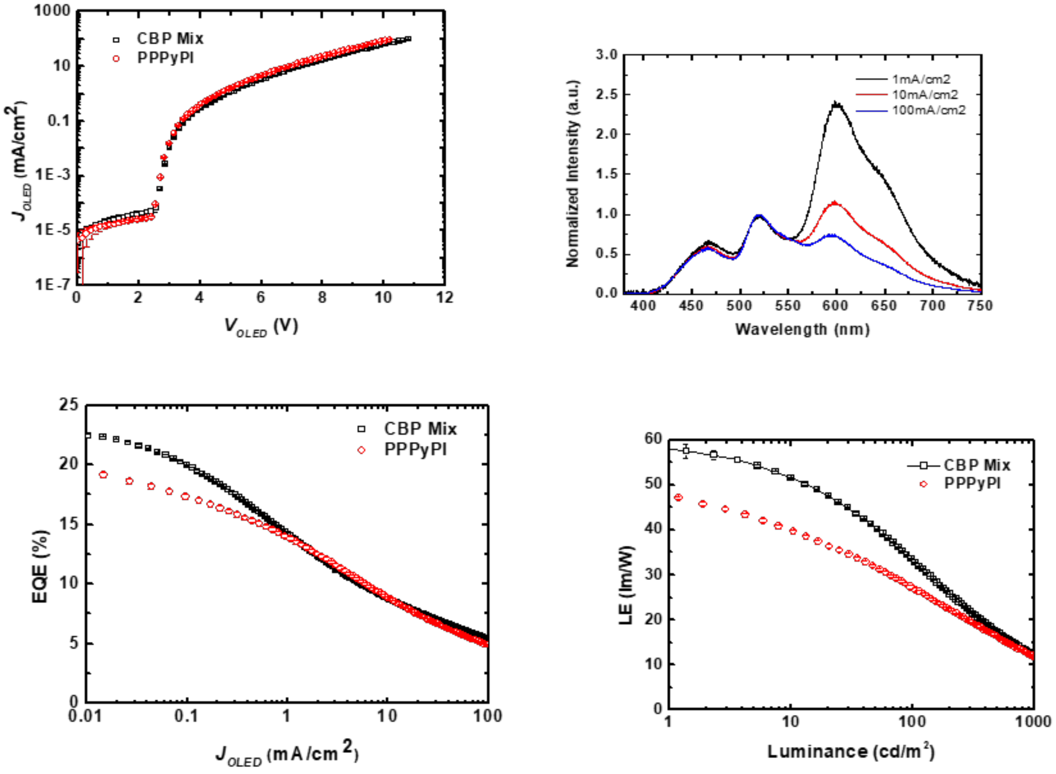


**Figure 3.3a:** The device structure and OLED data are shown for an EML that is a 50/50 mixture of CBP and I5.



The Mixed EML concept was explored further by using a gradient profile for the EML. Here the EML gradually shifted from 90% CBP and 10% I5 to 10% CBP and 90% I5. Sensor layers were placed at six positions within the device structure to probe the population of singlet and triplets in the stack. This data is shown in **Figure 3.3b**. Placing the ph-dopant in the right pace in the device leads to near flattening of the efficiency versus current profile.

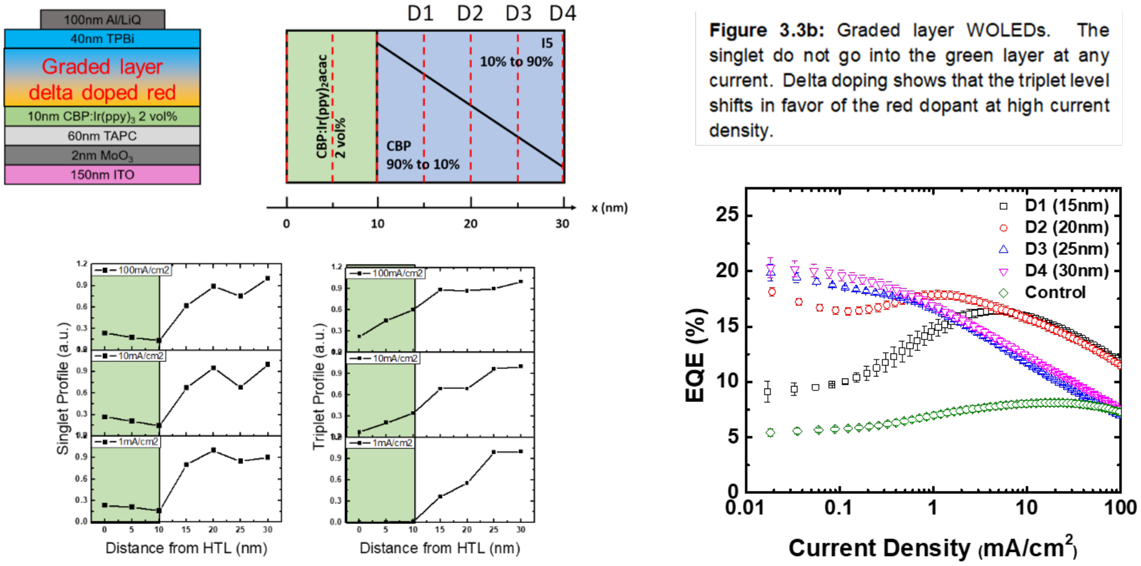


**Figure 3.3b:** Graded layer WOLEDs. The singlet do not go into the green layer at any current. Delta doping shows that the triplet level shifts in favor of the red dopant at high current density.

Milestone 4.3.2 (Projected M15, M24 60% Completed): Test lifetime of fl-blue OLED of Task 1.4.2. Demonstrate lifetime ($L_{70}$) > 25,000 hours at an initial luminance of 3,000 lm/m$^2$.

We tested both blue fl-doped and blue OLEDs that emit from a neat EML material (undoped), **Figure 4.3.2**. The initial brightness was 1000 nits. Both give high efficiency, but neither reaches the targeted device lifetime. We believe that part of the lifetime problem is due to the need for a more stable hole blocking material.

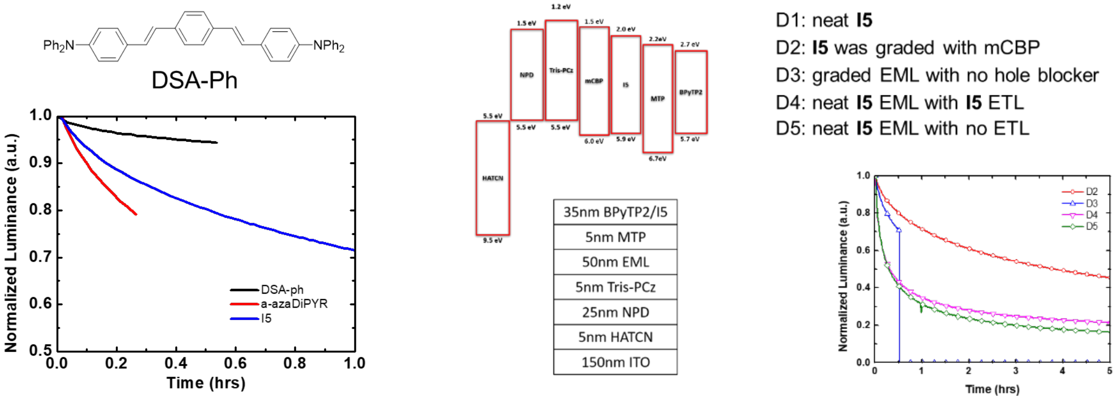


**Figure 4.3.2:** Lifetime data for doped (left) and undoped fluorescent blue OLEDs.

Milestone 4.4 (Projected M18, Completed M24): Test lifetime of fl/ph WOLEDs of Task 3.1.

This Milestone was targeted at measuring the lifetimes of a series of fl/ph WOLEDs, prepared with the previously report host CBP. Unfortunately, the efficiency of the CBP based WOLEDs were low due to triplet exciton trapping at the fl-dopant (**Figure 4.4**). WOLEDs were not available to give long operational lifetimes.

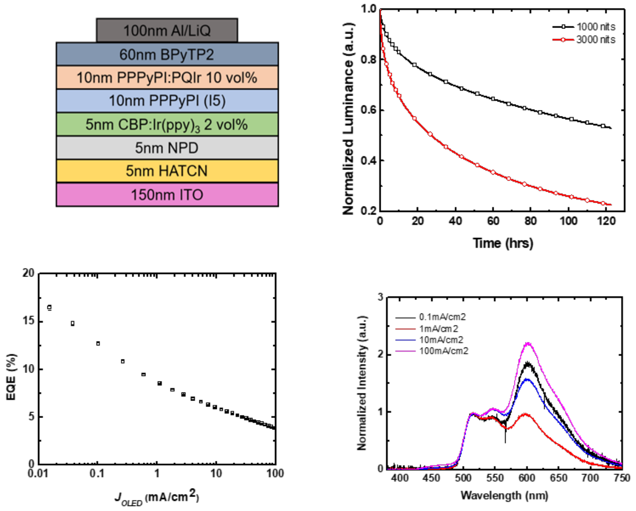


**Figure 4.4:** Lifetime data for hybrid WOLED.

Milestone 4.5 (Projected M21, M24 50% Completed ): Test lifetime of fl/ph WOLEDs of Task 3.2.

This Milestone was targeted at measuring the lifetimes of a series of fl/ph WOLEDs, prepared with host materials prepared in this program. Unfortunately, the efficiency roll off in these devices prevented us from achieving high luminance efficiency or high luminance. This prevented us from attaining long operational lifetimes.

Milestone 4.6 (M24 - not met): Test lifetime of fl/ph WOLEDs of Task 3.3. Demonstrate lifetime ($L_{70}$) > 25,000 hours at an initial luminance of 5,000 lm/m$^2$.

This Milestone was targeted at measuring the lifetimes of a series of fl/ph WOLEDs, prepared with host materials prepared in this program, as well as fl-dopants and tailored ph-dopants to achieve high luminance efficiency. The hybrid device suffered from carrier trapping at the phosphorescent dopant, so we prepared and tested a range of ph-dopants, and unfortunately all of them trapped electrons leading to a problem of efficiency roll off at high brightness. This prevented us from attaining long operational lifetimes at high brightness, so the milestone was not met.

End of project Milestone (Milestone not met): Demonstrate a hybrid fl/ph WOLED with an efficiency > 50 lm/W, CRI > 90 and lifetime of $L_{70}$ > 25,000 hrs at 5,000 lm/m$^2$.

We achieved high luminance efficiency at low brightness, but our devices all give high roll off in efficiency as the brightness is increased. Luminance levels of 5000 lm/W were not accessible with these devices, so the life tests could not be performed. Starting in M18 we began our research on a new architecture. This architecture consisted of a tandem pair or OLEDs, one a hybrid fl-blue/ph-red OLED and the other a ph-green OLED. We believe that this approach will help us eliminate the roll off problem and achieve the targeted lifetime.

**New approach initiated in the last two quarters**: In our proposal we described a single monolithic hybrid fl-ph WOLED that involved splitting the singlet and triplet excitons into 25% blue fluorescence and 75% green+red phosphorescence. To this end we developed blue fluorescent dopants with narrow singlet/triplet energy gaps and host materials to enable these hybrid devices. While we have made substantial progress toward our hybrid WOLED device, we have fallen short of our lifetime and efficiency goals. We have demonstrated that the host materials we have developed for the hybrid device are unlikely to meet our lifetime goals. Moreover, these host materials have triplet energies in the green, making them unsuitable for a full hybrid device. While we believe that a host material capable of hosting a blue fluorescent dopant and green+red phosphorescent dopants is achievable, we were concerned that it would not be possible to accomplish this in the time remaining in the program. To move closer to our program goals we shifted the focus of our program to a tandem device architecture, in which a fl-ph hybrid device will be stacked on top of a green phosphorescent device. The hybrid device will emit from fluorescent blue and phosphorescent red dopants, while the green phosphorescent device will be a broad green, tailing strongly into the yellow. This two OLED tandem device can achieve the color quality targets and we believe will get us close to the efficiency and lifetime targets of our program. The relaxed constraints on the host material for the hybrid device, *i.e.* it can have a high energy singlet and a green-to-yellow triplet, open the door to materials that may give good device lifetimes and efficiencies for both blue fluorescent and red phosphorescent devices. Our progress toward these tandem hybrid devices is given below.

Note that he hybrid fl/ph and green phosphorescent devices will be in a single stack, with a charge generation layer separating them (*i.e.* wired in series). The device fabrication of this tandem device will be similar to that of a single hybrid WOLED, and not add significant cost to a commercial product if the tandem structure is chosen over a single hybrid WOLED. It is important to stress that the core science that we proposed to explore and the reasons that the hybrid device was a desirable approach have not changed in this new approach. We are still working toward a hybrid fluorescent/phosphorescent device, which gives separate collection of singlet and triplet excitons, with the possibility of 100% exciton collection efficiency. The hybrid fluorescent/-phosphorescent OLED remains central to our studies and have been throughout the program.

## New Host Material for fl/ph hybrid WOLEDs

We have focused our attention on developing host materials for blue-fluorescence/red-phosphorescence, ultimately to be used in a tandem WOLED. In our previous report, we presented a set of host materials with fluorenone and biquinoline core structures. We found that the fluorenone compounds quenched the emission of our blue fluorescent dopant, **α-aD**, due to the observed emission coming from the host rather than our dopant in our film studies. From the biquinoline compound (**Figure 2.2a**), we moved forward with neat and doped film studies of 2,2'-biquinoline (**2BQ**)

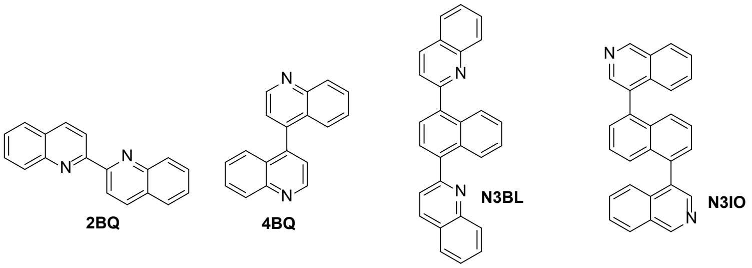


**Figure 2.2a:** Quinoline-based host materials for **α-aD** and **PQIr** for hybrid WOLED structure

since it has desirable lowest singlet excited ($S_1$) and lowest triplet excited ($T_1$) energies than 4,4'-biquinoline (**4BQ**). However, the photoluminescence quantum yield (PLQY) measurements of 1 wt% **α-aD**, 5 wt % **Ir(ppy)$_3$** and 5 wt% **PQIr** doped films gave values less than 10%. We attribute the low PLQY to the crystallization of the host. In this report, we explored addition of naphthalene bridged biquinolines to minimize the crystallinity of the system, while maintaining the triplet energy close to 2.5 eV.

**Table 2.2a**: Lifetime ($\tau_{fl}$) and fluorescence quantum yield (QY) of N3LB films

| N3BL | $\tau_{fl}$ (RT) | PLQY |
|---|---|---|
| 2-MeTHF Solution | 1.24 ns | 88% |
| Neat Film | 1.30 ns (66)<br>7 ns (34) | 24% |
| 1wt% **α-aD** doped | 3.40 ns | 69% |
| 5wt% **PQIr** | 1.3 μs | 73% |
| Neat Powder | - | 53% |

The two new host materials, **N3BL** and **N3IO**, are shown in **Figure 2.2a** and were synthesized using Suzuki-Miyaura conditions: 3-quinolineboronic acid pinacol ester with 1,4 bromonapthalene and 3-isoquinolineboronic acid pinacol ester with 1,5 bromonapthalene, respectively. DFT calculations suggests that the addition of naphthalene in both compounds maintains the target values of $T_1$ energy around 2.5 eV and $S_1$ energies between 3.5–3.9 eV, values ideal for our studies. **N3BL** was fully characterized in 2-Me-THF solution, solid powder, neat film and 1wt% **α-aD** doped film as shown in **Figure 2.2b** and **Table 2.2a**. Our data suggests that **N3BL** has >70nm bathochromic shift from its 2-Me-THF emission compared to the to the solid powder and neat film emission, as shown in **Figure 2.2b**. Currently, we believe it may be due to the pi-pi stacking of the aromatic quinoline and napthalene when in solid state, causing the bathochromic shift in these compounds. As a result, the absorbance of **α-aD** does not overlap with the emission of the host in solid state, which is necessary for Förster energy transfer between the host and the dopant. In addition, it is evident in **Figure 2.2b** that the emission of 1wt% **α–aD** doped in **N3BL** is predominantly from the host and not from the blue dopant. As a result, this led to the design of **N2IO** with the intention of making a naphthalene bridged-structure that mimics the interaction of the two quinoline core found in **2BQ** and **4BQ**. We expect that a complete 360 degree rotation in the connecting carbon-carbon bond in **2BQ** and **4BQ** is absent (or minimized) due to the steric hindrance and repulsion of the hydrogens in the opposing quinoline core. Since **4BQ** and **2BQ** did not have a bathochromic shift in the emission of their solution to solid state data, we hypothesize that mimicking a similar

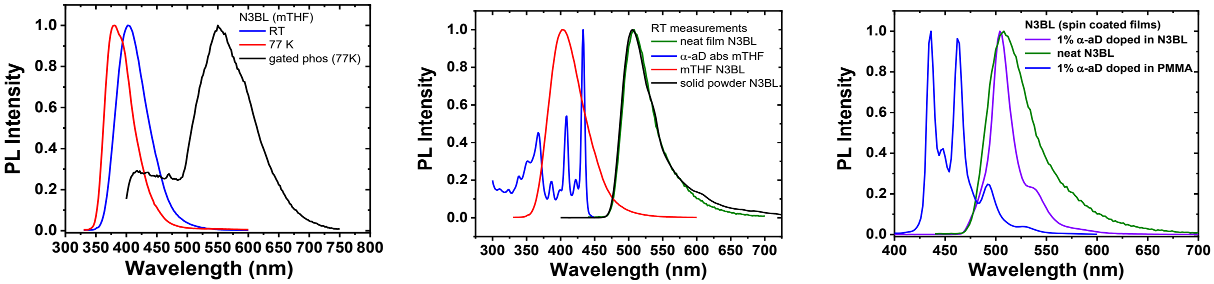


**Figure 2.2b**: Absorption and Emission Spectra of **N3BL** in solution (2-MeTHF), solid powder, neat film and 1wt% a-aD doped film.

mechanism in the naphthalene bridged structures can minimize the large bathochromic shift observe d in the **N3LB** host.

**N3IO** has been synthesized at USC but it requires multiple recrystallization for purification of the compound. We are currently in the process of subliming the compound after scale-up for further purification and characterization. However, measuring the purest sample we currently have, we can distinctly assign the emission belonging to **N3IO** and the impurity, as shown in **Figure 2.2c**. The red line in the excitation and the emission spectra belongs to **N3IO**, as expected from DFT studies. The emission spectra range of **N3IO** is between 350nm to 500nm which overlaps well with the absorbance of our blue fluorescent dopant; this relationship is ideal for an effective Förster energy transfer between the dopant and the host. If minimal bathochromic shift is observed for this material in the solid state, **N3IO** will be a good material to carry over for blue OLED and WOLED studies. Further studies will be conducted once the pure sample of **N3IO** is isolated, but we expect that **N3IO** will perform better than **N3LB** if it adapts a similar emission behavior observed in **4BQ** and **2BQ** from solution to solid.

Lastly, we have identified corannulene as another potential class of hosts for blue fluorescent and red phosphorescent dopants in our previous report. This is due to their rigidity, extended pi system, and do not have weak C–N bonds suggesting good stability and charge transport properties for OLED. We have shown that the triplet energy of corannulene in the solid state ($E_{Tsolid}$ = 500nm) is low enough to accept triplet excitons from **α-aD** and high enough to transfer the triplets to **PQIr**. Despite these excellent properties, we have shown that corannulene suffers from rapid crystallization as neat material due to its low molecular weight. For this reason, xylyl moiety was added to corannulene (**X-cor**) to increase the molecular mass to decrease the chance of crystallization. The xylyl group twists out of plane and hence did not affect the photophysical and electrochemical properties of corannulene.

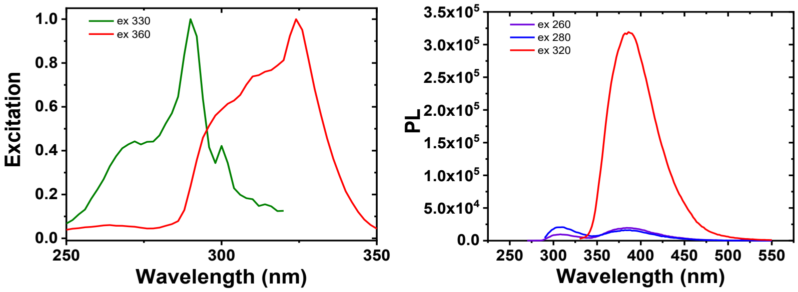


**Figure 2.2c:** Excitation and Emission Spectra (PL) of N3IO where the red lines in both spectra corresponds to the N3IO whereas excitation between 250nm-300nm (green) and emission between 280nm-320nm corresponds to the impurity.

In this quarter, we have synthesized **X-cor** in large scale and purified it for photophysical, electrochemical and electroluminescence studies. As a start, we first investigate whether **X-cor** can host a green phosphor for three-color RGB WOLED application or a yellow phosphor for two-color WOLED application. The triplet energy ($E_{Tsolid}$ = 2.50 V) of **X-cor** is close in energy to the triplet energies of a green (Bis[2-(2-pyridinyl-N)phenyl-C](acetylacetonato)iridium(III) ($Ir(ppy)_2acac$)) and a yellow phosphor ($Ir(bt)_2acac$)). To investigate the efficiencies of these phosphors in **X-cor** and in a reference host (*m*CBP), doped films of these phosphors in **X-cor** and *m*CBP were prepared. First, $Ir(ppy)_2acac$ was doped into *m*CBP and **X-cor** at 10 vol% doping concentration. Absorption and emission spectra of the films are shown in **Figure 2.2e**. The

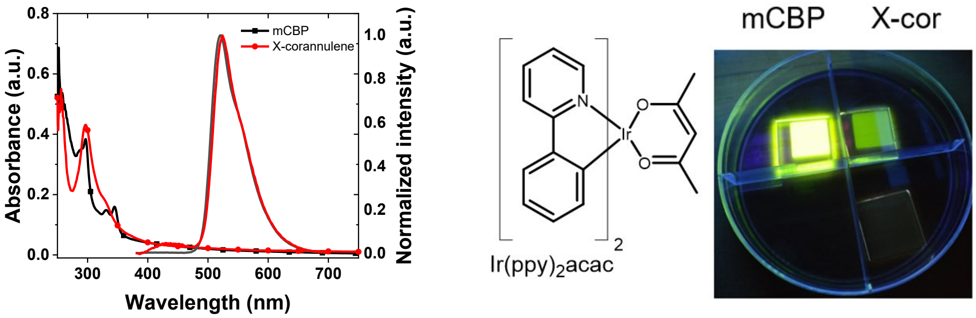


**Figure 2.2e**. Absorption and emission spectra of Ir(ppy)$_2$acac:*m*CBP 10% and Ir(ppy)$_2$acac:**X-cor** 10% vapor deposited film (Left). Molecular structure of Ir(ppy)$_2$acac and pictures of the films (Right).

**Table 2.2c**. PLQY and lifetime of Ir(ppy)$_2$acac:*m*CBP 10% and Ir(ppy)$_2$acac:**X-cor** 10% vapor deposited film

| | PLQY (%) | Lifetime (μs) |
|---|---|---|
| Ir(ppy)$_2$acac:*m*CBP 10wt% | 90 | 1.3 |
| Ir(ppy)$_2$acac:**X-cor** 10wt% | 10 | Long |

absorption spectrum of Ir(ppy)$_2$acac is dominated by the hosts spectra, whereas the emission (540 nm) solely comes from the phosphor indicating effective exciton trapping by the phosphor. The photoluminescence quantum yield (PLQY) and emission lifetime of the films are summarized in **Table 2.2c**. The PLQY of Ir(ppy)$_2$acac dopped into **X-cor** is very low (PLQY = 10%) compared to efficiency *m*CBP doped films (PLQY = 90%). Lifetime of the film with **X-cor** was also not in the microsecond range, further suggesting that **X-cor** quenches the emission of Ir(ppy)$_2$acac. Based on the triplet energy of **X-cor**, quenching of Ir(ppy)$_2$acac emission is to be expected. This host

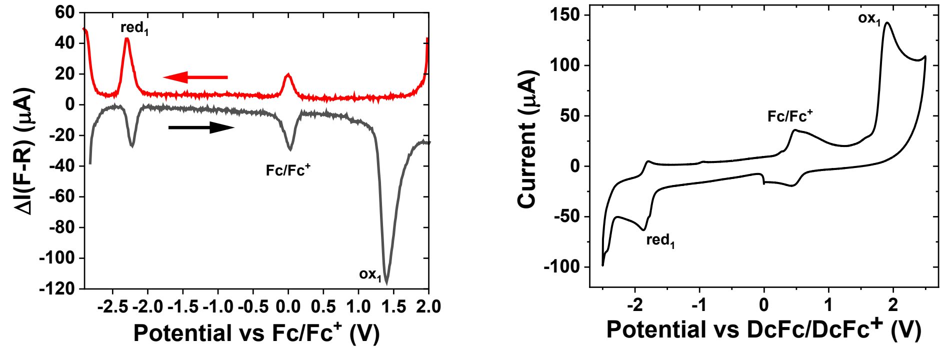


**Figure 2.2g**. Differential Pulse Voltammetry (Left) and Cyclic Voltammetry (Right) of **X-cor**.

**Table 2.2e.** Reduction, oxidation potential, LUMO and HOMO values of **X-cor**.

| | $E_{ox1}$ (Fc/Fc$^+$) | $E_{red1}$ (Fc/Fc$^+$) | HOMO (eV) | LUMO (eV) |
|---|---|---|---|---|
| **X-cor** | 1.4 V | -2.3 V | -6.4 | -2.1 |

is being explored for blue-fl/red-ph hybrid WOLEDs. In order to see how close the phosphorescent dopant can be to the triplet energy of **X-cor** we explored a yellow phosphorescent dopant in this hist. A yellow phosphor ($Ir(bt)_2acac$) was vapor deposited into *m*CBP and **X-cor** at 10% doping level. As shown in **Figure 2.2f**, emission of two films comes exclusively from the $Ir(bt)_2acac$. Furthermore, quantum yields and lifetime of the two films rarely change, suggesting that $Ir(bt)_2acac$ is not quenched by **X-cor**. As a result, **X-cor** can be a promising host material for **α-aD** and $Ir(bt)_2acac$, implying two color (B and Y) non stacked WOLED is achievable with **X-cor**.

Prior to making devices, transport levels of **X-cor** are first determined. As shown in **Figure 2.2g**, cyclic voltammetry and differential pulse voltammetry were conducted to measure the oxidation and reduction potentials of **X-cor** with respect to ferrocene (**Table 2.2e**), eventually estimating HOMO and LUMO values of **X-cor**. HOMO and LUMO of **X-cor** turned out to be -6.4 eV and -2.1 eV respectively. Deep LUMO value of **X-cor** (-2.1 eV) might contribute to less direct charge trapping on **PQIr**, promising to utilize conventional host-guest system. Conventional co-doping system is promising to alleviate severe efficiency roll-off at high current density that results from ultra-thin layer of **PQIr**. Hosting ability of **X-cor** as a host for **α-aD** was tested in the device as shown in **Figure 2.2h**. **α-aD** was doped into *m*CBP (reference) and X-cor with 1 vol% doping condition. Voltage -current density plot shows that the device utilizing **X-co**r as a host is more conductive than *m*CBP host-based device. This increase in conductivity is probably due to deeper LUMO of **X-cor** than that of **α-aD**, allowing the **X-cor** to transport electrons. In contrast, electrons are transported by **α-aD** in *m*CBP based devices due to shallower LUMO of *m*CBP compared to that of **α-aD**. EQEs of two devices are comparable, showing maximum EQE at 3% and 2% for *m*CBP and **X-cor** device, respectively. The lower EQE **X-cor** based devices is probably due to poor charge balance in the emissive layer. Another plausible rationale is exciplex formation at the interface of TAPC/X-cor (HOMO of TAPC and LUMO of **X-cor**), resulting in drop of the efficiency. This argument can be further supported by the presence of the low-energy emission peak starting from 525nm for **X-cor**-based device. **X-cor** is further employed as a host for a red phosphor (**PQIr**). mCBP is used as a reference host and the results are summarized in in **Figure 2.2i**. Conductivity of two devices is similar presumably due to HOMO and LUMO of PQIr are nested by both *m*CBP and **X-cor**. Overall device efficiencies are comparable for both cases, suggesting that PQIr is not quenched by **X-cor**. This can be further confirmed by the identical electroluminescence spectrum of the two devices. Based on the device performances, **X-cor** is a promising host material for newly suggested stacked WOLED.

### Task 2.3: Metal-free Charge Generation Layer for fl/ph hybrid WOLEDs

An efficient charge generation layer (CGL) is essential for a stacked WOLED. A wide range of CGLs including metal-metal, metal oxide, organic-metal and p/n doping organic bilayer type of CGLs have been reported for OLEDs. Metal-doped CGLs are not ideal due to high thermal evaporation temperature of metals, and the diffusivity of the metal ions in the organic film. p-type/n-type CGLs have been investigated in OLEDs which eliminate the problems of thermal damage and insatbilty due to metal ion diffusion which are associated with the metal-doped CGLs. 1,4,5,8,9,11-Hexaazatriphenylene hexacarbonitrile (HATCN) is well-known n-type material by virtue of its deep LUMO level. Combination with p-type material such as TAPC is well studied as

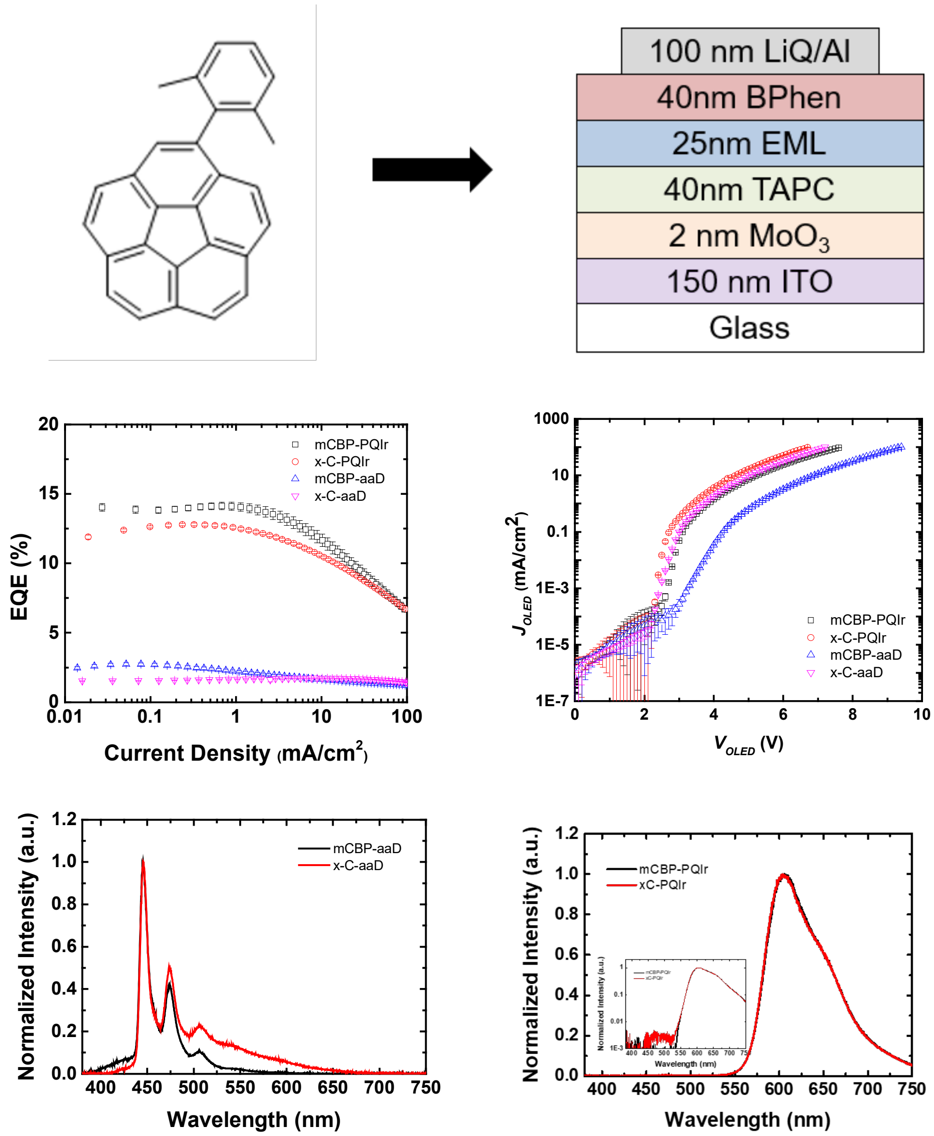


**Figure 2.2i**: xylyl-corannulene test device and performance

a working CGL in OLEDs.[*] Herein, functionality of HATCN/m-MTDATA as a CGL is investigated to apply into the new hybrid stacked WOLED structure as provided in **Figure 2.3a** and **Table 2.3a**. TAPC (HTL), Bphen (ETL) are inserted next to cathode and anode respectively to prevent injection of charges from the electrodes. HATCN/m-MTDATA CGL is inserted in device 2 but no current flow is detected owing to large energy gap between HATCN and Bphen. Current flow is

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[*] Dai, Y. F.; Zhang, H. M.; Zhang, Z. Q.; Liu, Y. P.; Chen, J. S.; Ma, D. G., Highly efficient and stable tandem organic light-emitting devices based on HAT-CN/HAT-CN:TAPC/TAPC as a charge generation layer. *Journal of Materials Chemistry C* **2015,** *3* (26), 6809-6814. Sun, H. D.; Guo, Q. X.; Yang, D. Z.; Chen, Y. H.; Chen, J. S.; Ma, D. G., High Efficiency Tandem Organic Light Emitting Diode Using an Organic Heterojunction as the Charge Generation Layer: An Investigation into the Charge Generation Model and Device Performance. *Acs Photonics* **2015,** *2* (2), 271-279.

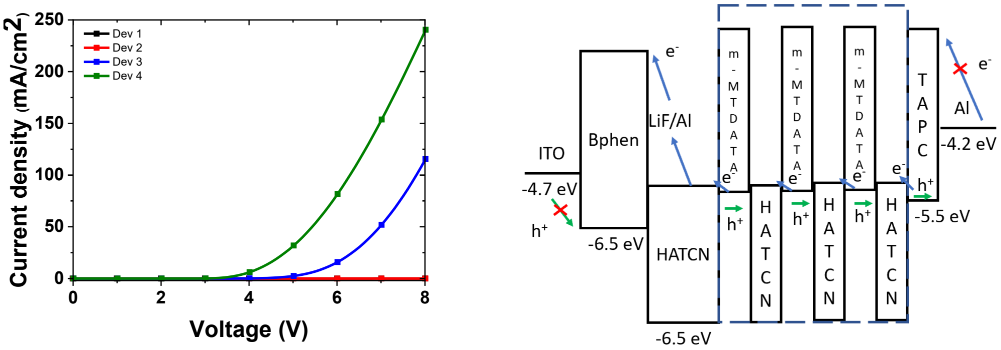


**Figure 2.3a**. J-V characteristic curve for device 1-4 (Left). HOMO/LUMO levels of materials used with flow of charges (Right).

**Table 2.3a** Device architectures to investigate functionality of HATCN/m-MTDATA as a CGL

| Device | Layer structures |
|---|---|
| Device 1 | ITO/Bphen(40 nm)/TAPC(60 nm)/Al(100 nm) |
| Device 2 | ITO/Bphen(40 nm)/HATCN(15 nm)/m-MTDATA(15 nm)/TAPC(30 nm) /Al(100 nm) |
| Device 3 | ITO/Bphen(40 nm)/LiF(1 nm)/Al(1 nm)/HATCN(15 nm)/m-MTDATA(15 nm)/TAPC(30 nm)/Al(100 nm) |
| Device 4 | ITO/Bphen(40 nm)/LiF(1 nm)/Al(1 nm)/HATCN(15 nm)/HATCN:m-MTDATA 2:1 mixing(15 nm)/TAPC(30 nm)/Al(100 nm) |

**Table 2.3b**. Device structure of non-stacked and stacked device.

| Device | Device structure with thickness (nm) |
|---|---|
| Non-stacked Ir(ppy)$_3$ device | TAPC(20)/CBP:Ir(ppy)$_3$ 10% (15)/Bphen(30)/LiF(1)/Al(100) |
| Non-stacked PQIr device | TAPC(20)/CBP:PQIr 10% (15)/Bphen(30)/LiF(1)/Al(100) |
| Stacked device | TAPC(20)/CBP:Ir(ppy)$_3$ 10% (15)/Bphen(30)/LiF(1) /Al (1)/HATCN:m-TDATA 2:1 (15)/TAPC (20)/Bphen (30)/LiF (1)/Al (100) |

detected when LiF/Al is introduced between these two layers due to improvement in electron injection (Device 3). Furthermore, mixed layer (HATCN:m-MTDATA) creates charges more efficiently than HATCN/m-MTDATA. The HATCN:m-MTDATA unit is further tested in actual stacked WOLED as shown in **Figure 2.3b** and **Table 2.3b**. Monochromatic device with Ir(ppy)$_3$ and PQIr are made as non-stacked devices and stacked device using CGL is also fabricated to assess the utility of CGL in stacked WOLED. **Figure 2.3b** indicates that EQE of stacked device is proportional to sum of non- stacked devices, proving CGL functions normally. Luminance of

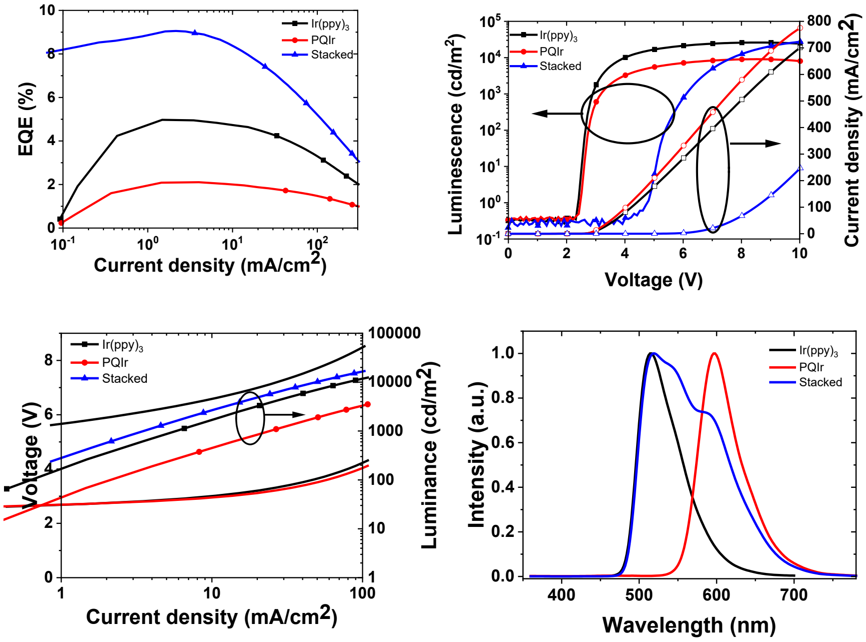


**Figure 2.3b**. Device performances of non-stacked and stacked devices

stacked device at a given current density is higher than that of non-stacked devices, also suggesting charges are created by CGL.

## Modeling Tandem Hybrid/Phosphorescent WOLED

Creating a reliable hybrid WOLED is still limited by the lack of a stable hole blocking material. As an alternative, we have proposed last quarter to make a stacked device using a phosphorescent green cell, a hybrid red and blue cell, and a charge generation layer. Making a stacked device has an advantage in lifetime due to its low current density but is tricky due to the enhanced cavity induced by stacking, where optical outcoupling of the emissive cells to air modes become an issue. Therefore, we have researched a model for such a device using dyadic Green's functions for outcoupling calculations.

The example structure of the stacked WOLED is shown in **Figure 3.2f**. We assumed a single dipole layer for each color, where the simulated wavelengths were 450nm, 510nm, and 610nm for blue, green, and red emitters used in our device, respectively. The quantum yield of emitters was set to 25% or blue and 100% for green and red. The orientation of the molecules

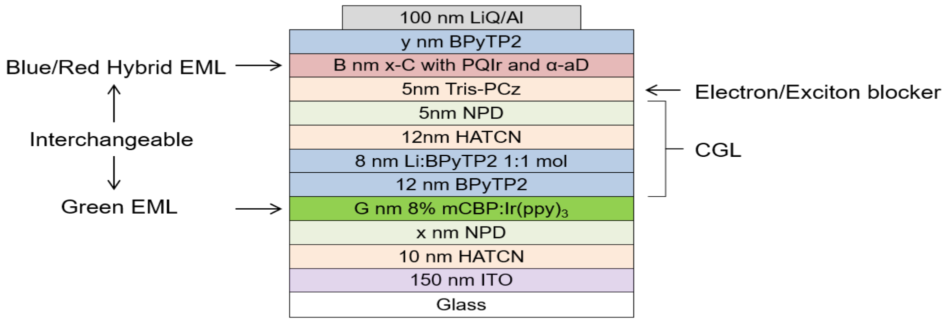
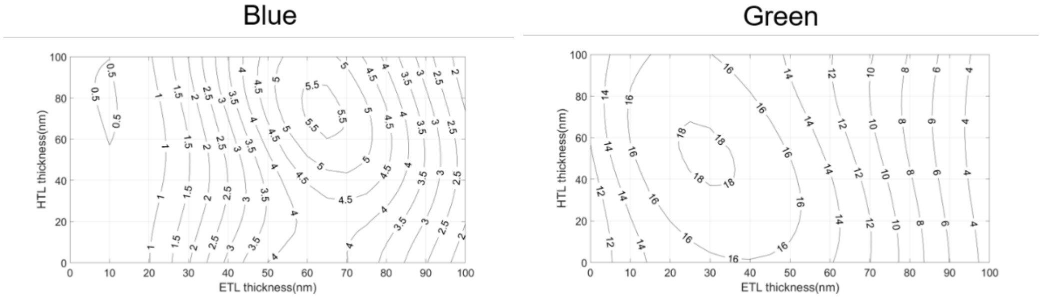


**Figure 3.2f**: Example structure of stacked hybrid WOLED

was chosen to be random. Additionally, the positions of the cells are interchangeable to choose whichever is favorable for high efficiency and color balance. By calculating for the external quantum efficiency of all emitters we can guess the output spectrum and therefore the color balance of the stacked hybrid WOLED. The efficiency ratio of blue:green:red should be in the range of 1:2:4 for high color rendering index.

Layer thicknesses in the example structure were set identical to the example structure in **Figure 3.2f**, where the charge generation layer was adopted from a stacked device published from our group. Using this structure, we simulated external quantum efficiency for the thicknesses of the bottom NPD and top BPyTP2 while varying the thicknesses of both emissive layers. Simulation results are maximum efficiency points for all three colors combined. The range of simulation for transport layer thicknesses is from 0 to 100nm and emissive layer thicknesses from 15 to 50nm.

We started with the green cell on the bottom and blue/red cell on top. The maximum efficiency for this scenario is obtained when both emissive layers are 30nm thick. The external quantum efficiency plots for all colors is shown in **Figure 3.2g**. However, an optimal color balance for white light using this stack was never achieved within the simulation range. The maximum efficiency points of all emitters do not converge.


Blue Green

Red

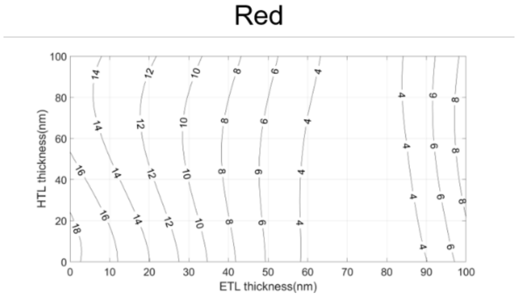


**Figure 3.2g**: Calculated external quantum efficiency plots for all emitters with bottom green cell and top blue/red cell

We then explored the stack with the green cell on the top and red/blue cell on the bottom. The maximum efficiency for this case is achieved when the green emissive layer is 20nm thick and red/blue emissive layer is 40nm thick. Calculation results are shown in **Figure 3.2h**. For this case, a good color balance of blue:green:red photon ratio of 1:1.5:3.2 can be obtained when NPD is 20nm thick and BPyTP2 is 10nm thick. However, similarly to the previous case, the external quantum efficiency peaks of both cells do not converge where the phosphorescent green cell has only 7.8% external quantum efficiency due to cavity mode and plasmon mode. The low efficiency even when perfect emitters are assumed indicates that the resulting power efficiency will be low.

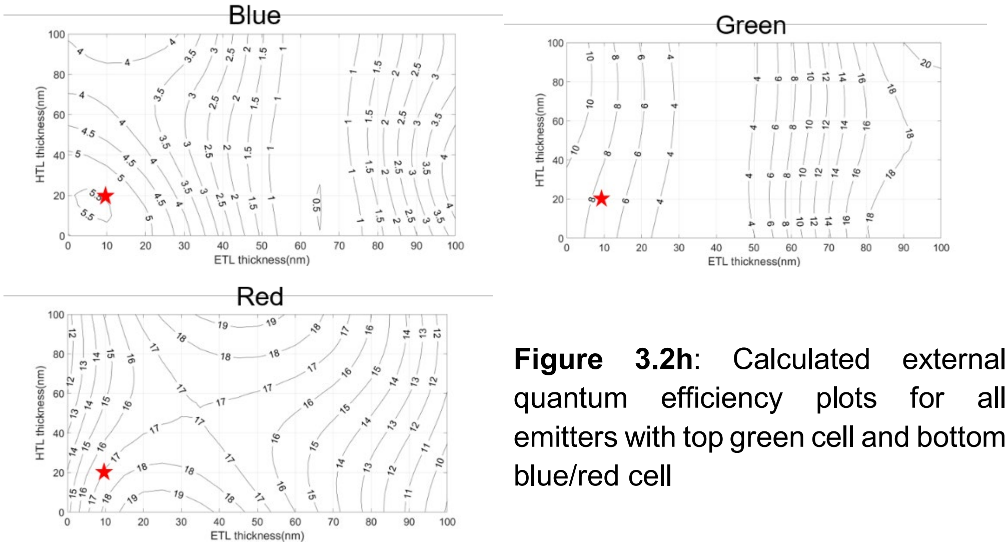


**Figure 3.2h**: Calculated external quantum efficiency plots for all emitters with top green cell and bottom blue/red cell

The problem for both cases is that the peak external quantum efficiencies never converged over the simulation range. Therefore, we modified the code to include variation of the charge generation thicknesses as well. The highest efficiency of this scenario was obtained with the blue/red cell on top and green cell on the bottom and the thicknesses of both NPD and BPyTP2 inside the charge generation layer set to 40nm. As can be seen in **Figure 3.2i**, although the peak external quantum efficiencies of all emitters do not perfectly overlap, the highest overall external quantum efficiency has been achieved where blue EQE is 5.2%, green EQE is 16.9%, and red EQE is 20.4% when NPD is 80nm thick and BPyTP2 is 40nm thick. All thicknesses are shown in the device diagram in **Figure 3.2i**. However, the color balance still requires improvement because we have too many green photons compared to the intensities of blue and red. Hence, we decided to add another blue/red cell for better color balance. Also, adding another stack further reduces drive current which may enhance device lifetime as well.

Calculation results for the three-stack device is shown in **Figure 3.2j**. All layer thicknesses for this scenario are also shown in the figure. The numbers 1 and 2 in the external quantum efficiency plots indicate the topmost red/blue cell and the center red/blue cell, respectively. Although it was not possible to have all peaks of the external quantum efficiency to converge, the overall external quantum efficiency for each emitter was maximized: the first blue/red cell with 3.3% and 19.2%, the second blue/red cell with 3.1% and 19.1%, and the green cell with 14.5% external quantum efficiency. We obtain a photon ratio of 1:2.3:6 with this configuration. We have not fabricated any stacked WOLEDs yet, but the calculation results show that is a possible scenario in creating stable and efficient hybrid WOLEDs. This work will be carried on with support from the Universal Display Corporation.

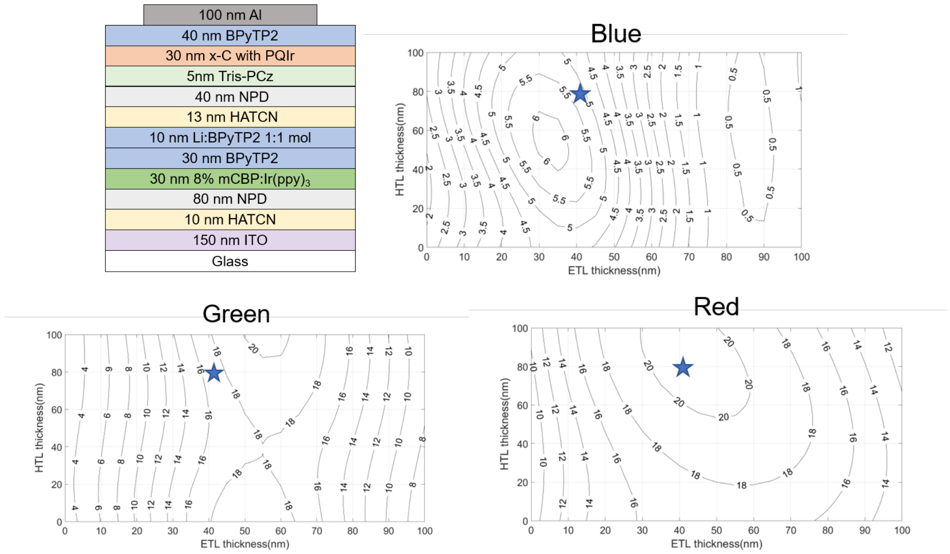


**Figure 3.2i**: Calculated external quantum efficiency plots for all emitters with modified charge generation layer thicknesses

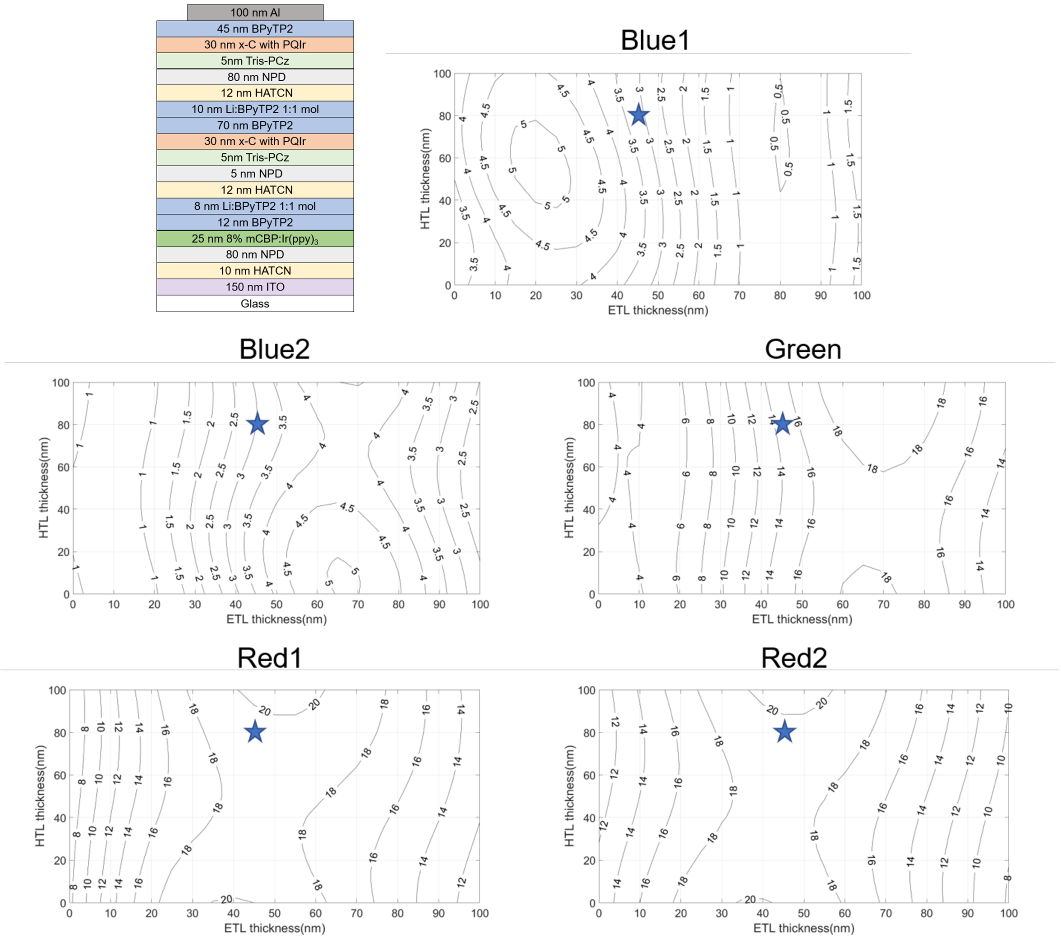


**Figure 3.2j**: Calculated external quantum efficiency plots for all emitters with bottom green cell and top blue/red cell

| | |
|---|---|
| **Recipient:** | **University of Southern California** |
| **DOE Award #:** | **DE-EE0008244** |

## I. Major Task/Milestone Schedule

| SOPO Task # M.S. # | Task Title and Milestone Description | Performer | Task Start Date | Milestone Completion Date | | | | Progress Notes |
|---|---|---|---|---|---|---|---|---|
| | | | | Original Planned | Revised Planned | Actual | Percent Complete | |
| | **Budget Period 1** | | | | | | | |
| 1.1 / (M 1.1) | Model fl dopants | USC | | Q1 | | Q1 | 100% | |
| 1.2 / (M 1.2.1) | Prepare 2 fl dopants | USC | | Q2 | | Q2 | 100% | |
| 2.1 | Model fl/ph WOLED hosts | USC | | Q2 | | Q2 | 100% | |
| 4 / (M 4.1) | Lifetime: publ. fl/ph WOLED | UM | | Q2 | | Q2 | 100% | |
| 1.2 / (M 1.2.2) | Prepare 4 fl dopants | USC | | Q3 | | Q3 | 100% | |
| 3 / (M 3.1) | WOLED: Fl dopant from Task 1 | UM | | Q3 | | Q3 | 100% | Conventional host materials limited efficiencies. |
| 4 / (M 4.2) | Lifetime of OLEDs in Task 1.3 | UM | | Q3 | Q4 | Q5 | 100% | Lifetime measured, but we need a better hole blocker. |
| 1.3 / (M 1.3) | Prepare & test blue OLEDs | UM/USC | | Q4 | | Q3 | 100% | |
| 2 / (M 2.2.1) | Prepare h+ transport hosts | USC | | Q4 | | Q3 | 100% | |
| 3 / (M 3.2) | 3.1 + host from Task 2 | USC/UM | | Q4 | Q7 | Q7 | 100% | Lifetime target not met. |
| 4 / (M 4.3.1) | Lifetime of OLEDs with new host | UM | | Q4 | Q7 | Q7 | 80% | |
| GO / NO GO | Performance of hybrid fl/ph WOLED | USC/UM | | Q4 | | Q4 | 100% | |
| | | | | | | | | |
| | **Budget Period 2** | | | | | | | |
| 2.2 (M 2.2.2) | Prepare e- transport hosts | USC | | Q5 | | Q5 | 100% | |
| 4 / (M 4.3.2) | Lifetime of OLEDs in Task 1.4.2 | UM | | Q5 | Q8 | | 60% | Tested multiple devices, did not meet lifetime targets. |
| 1.4 (M 1.4.1) | Blue OLED in h+ WOLED host | USC/UM | | Q6 | | Q6 | 100% | |
| 4 / (M 4.4) | Lifetime of WOLEDs in Task 4.1 | UM/USC | | Q6 | Q8 | Q8 | 100% | Hiighly efficient and color stalbe WOLEDs were not available. |
| 1.4 / (M 1.4.2) | Blue OLEDs in e- WOLED host | USC/UM | | Q7 | | Q7 | 100% | |
| 3 / (M 3.3) | 3.2 + optimized ph dopants | USC | | Q7 | Q8 | Q8 | 60% | Prepared several, but did not see an increase in efficiency or decrease in roll off. |
| 4 / (M 4.5) | Lifetime of OLEDs in Task 4.2 | UM | | Q7 | Q8 | | 50% | An efficient and long lived hybrid host is needed. |
| 4 / (M 4.6) | Lifetime of OLEDs in Task 4.3 | UM | | Q8 | | | 0% | An efficient and log lived host is needed. |
| Final | Performance of hybrid fl/ph WOLED | USC/UM | | Q8 | | | 40% | Decreased roll off, but did not hit performance targets. |
| | | | | | | | | |

**Recipient:** University of Southern California
**DOE Award #:** DE-EE0008244

**Reporting period:** 7/1/2019 to 9/30/2019
**Click Here ▲**

**Instructions:**

1) Set the Dates: Change the years listed in Column A to correspond to your project and delete the excess rows. If your project quarter is other than calendar quarters, you need to adjust the formulas in Cell C12 and D12 and then copy and paste them for the rows below. Call your TPO for assistance.
2) Initial Spend Plan: Enter the initial Spend Plan for the entire project in Columns A and C (gray columns). Once entered, these amounts will NOT be changed for the entire period of the award.
3) Reporting Period: Select the reporting period (the past quarter) by clicking on the PINK cell above and then click on the down arrow to the right of the cell. Cells below will turn green for selected reporting period.
4) Fill in **actual outlays** for **past** quarters in the columns B. and D (green cells). (may not match the SF425 Financial Status Report)
5) Adjust **projected outlays** for **present and all future** quarters columns B and D (blue cells).

| **II. Project Spend Plan** | | | | **A. Federal Share Initial Plan totals $801,092** | **B. Federal Share Updated Actuals & Plan** | **Cumulative Federal Share** | **C. Recipient Share Initial Plan totals $225,309** | **D. Recipient Share Updated Actuals & Plan** | **Cumulative Recipient Share** |
|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Quarter** | **From** | **To** | | | | | | |
| 2017 | Q1 | 1/1/2017 | 3/31/2017 | | $0.00 | $0.00 | | $0.00 | $0.00 |
| 2017 | Q2 | 4/1/2017 | 6/30/2017 | | $0.00 | $0.00 | | $0.00 | $0.00 |
| 2017 | Q3 | 7/1/2017 | 9/30/2017 | | $0.00 | $0.00 | | $0.00 | $0.00 |
| 2017 | Q4 | 10/1/2017 | 12/31/2017 | $50,000.00 | $32,576.64 | $32,576.64 | $27,911.50 | $16,247.64 | $16,247.64 |
| 2018 | Q1 | 1/1/2018 | 3/31/2018 | $117,030.00 | $55,926.87 | $88,503.51 | $27,911.50 | $24,687.11 | $40,934.75 |
| 2018 | Q2 | 4/1/2018 | 6/30/2018 | $117,030.00 | $68,195.77 | $156,699.28 | $27,911.50 | $15,047.01 | $55,981.76 |
| 2018 | Q3 | 7/1/2018 | 9/30/2018 | $117,032.00 | $137,942.15 | $294,641.43 | $27,911.50 | $29,357.88 | $85,339.64 |
| 2018 | Q4 | 10/1/2018 | 12/31/2018 | $100,000.00 | $103,125.29 | $397,766.72 | $28,415.75 | $45,792.64 | $131,132.28 |
| 2019 | Q1 | 1/1/2019 | 3/31/2019 | $100,000.00 | $140,348.77 | $538,115.49 | $28,415.75 | $24,970.28 | $156,102.56 |
| 2019 | Q2 | 4/1/2019 | 6/30/2019 | $100,000.00 | $174,578.75 | $712,694.24 | $28,415.75 | $16,072.05 | $172,174.61 |
| 2019 | Q3 | 7/1/2019 | 9/30/2019 | $100,000.00 | $88,397.76 | $801,092.00 | $28,415.75 | $53,271.72 | $225,446.33 |
| 2019 | Q4 | 10/1/2019 | 12/31/2019 | | | $801,092.00 | | | $225,446.33 |
| 2020 | Q1 | 1/1/2020 | 3/31/2020 | | | $801,092.00 | | | $225,446.33 |
| **Totals** | | | | **$801,092.00** | **$801,092.00** | $801,092.00 | **$225,309.00** | **$225,446.33** | $225,446.33 |
| | | | | **Updated Federal Spend Plan** | | | **Updated Recipient Spend Plan total** | | |

*Delayed expenses that were charged in September 2019 are now reflected in our final report. Cost-share expenditures for the University of Michigan that were delayed, have been recaptured and expensed during the last quarter. Additionl cost-share expenses accrued than from inital planned budget due to increase in fringe and salary lines for annual cost of living increases.

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|---|---|
| **Recipient:** | **University of Southern California** |
| **DOE Award #:** | **DE-EE0008244** |

## III. Spending Summary by Budget Category

|  | **Approved Budget per SF-424A** |  |  | **Actual Expenses** |  |
|---|---|---|---|---|---|
| **Budget Categories per SF-424a** | **BP 1** | **BP 2** |  | **This Quarter** | **Cumulative** |
| a. Personnel | $114,511 | $117,946 |  | $17,261 | $237,370 |
| b. Fringe Benefits | $12,840 | $13,226 |  | $4,884 | $30,399 |
| c. Travel | $6,724 | $6,028 |  | $1,842 | $10,999 |
| d. Equipment | $0 | $0 |  | $0 | $0 |
| e. Supplies | $15,361 | $22,546 |  | $5,377 | $30,497 |
| f. Contractual | $249,918 | $250,083 |  | $93,219 | $500,001 |
| g. Construction | $0 | $0 |  | $0 | $0 |
| h. Other | $0 | $0 |  | $0 | $0 |
| **i. Total Direct Charges** | **$399,354** | **$409,829** |  | **$122,583** | **$809,266** |
| j. Indirect Charges | $113,384 | $103,834 |  | $19,087 | $217,273 |
| **k. Total Charges** | **$512,738** | **$513,663** |  | **$141,670** | **$1,026,539** |
| DOE Share | $401,092 | $400,000 |  | $88,398 | $801,093 |
| Cost Share | $111,646 | $113,663 |  | $53,272 | $225,446 |
| **Cost Share Percentage** | 21.8% | 22.1% |  | 37.6% | 22.0% |

*Delayed expenses that were charged in September 2019 are now reflected in our final report. Cost-share expenditures for the University of Michigan that were delayed, have been recaptured and expensed during the last quarter. Additional cost-share expenses accrued than from inital planned budget due to increase in fringe and salary lines for annual cost of living increases.

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|---|---|
| **Recipient:** | **University of Southern California** |
| **DOE Award #:** | **DE-EE0008244** |

| IV. Funding by Task | FY 17($) | FY18 ($) | FY19 ($) | Task Total ($) |
|---|---|---|---|---|
| **Task 1: Blue fl dopants with ΔEST <0.4 eV>** | $33,016 | $160,059 | $113,057 | $306,132 |
| **Task 2: Host materials for hybrid fl/ph WOLEDs (M4-M12)** | $7,741 | $67,382 | $63,540 | $138,663 |
| **Task 3: Study of Hybrid WOLEDs** | $4,033 | $151,303 | $204,214 | $359,550 |
| **Task 4: Device lifetime measurement (M4-M24)** | $4,033 | $101,331 | $116,830 | $222,194 |
| **Total** | **$48,824** | **$480,074** | **$497,642** | **$1,026,539** |

## V. Accomplishments

***Note: This is a cummulative list of accomplishments related to this award. Accomplishments made within this quarter should be highlighted in yellow. See the following tab for examples.***

**Recipient:** University of Southern California
**DOE Award #:** DE-EE0008244

| | **Journal Articles** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Full Author List** | **"Article Title"** | **Journal Name** | **Volume Number** | **No #** | **pp. (##-##)** | **Year** | **DOI** |
| A | Abegail C. Tadle, Karim A. El Roz, Chan Ho Soh, Daniel Sylvinson M.R., Stephen R. Forrest, and Mark E. Thompson | Tuning the Photophysical and Electrochemical Properties of Aza-boron-dipyridylmethene Complexes for Fluorescent Blue OLEDs | *N/A* | *N/A* | *N/A* | *N/A* | *Manuscript in Preparation* | *N/A* |
| | Muazzam Idris, Chan Ho Soh, Moon Chul Jung, Peter I. Djurovich, Stephen R. Forrest, and Mark E. Thompson | Tuning Singlet and Triplet Excited State Energies and Frontier Orbitals of Imidazole Host/Emitter for Hybrid White OLEDs | *N/A* | *N/A* | *N/A* | *N/A* | *Manuscript in Preparation* | *N/A* |
| | Chan Ho Soh, Muazzam Idris, Caleb Coburn, Mark E. Thompson, and Stephen R. Forrest | Reducing Efficiency Roll off in Hybrid White Organic Light Emitting Devices | *N/A* | *N/A* | *N/A* | *N/A* | *Manuscript in Preparation* | *N/A* |
| | Daniel Sylvinson M.R., and Mark E. Thompson | Systematic Exploration of Large Chemical Subspaces for Organic Optoeletronic Applications Aided by DFT and Machine Learning | *N/A* | *N/A* | *N/A* | *N/A* | *Manuscript in Preparation* | *N/A* |

| | **Books** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| B | **Full Author List** | **Book Title** | **Edition** | | **Publisher** | **# pages** | **Year** | **ISBN** |
| | None | | | | | | | |

| | **Book Chapters** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| C | **Full Author List** | **"Chapter Title", Chapter # in Book Title** | **Edition** | **Full List of Editors** | **Publisher** | **pp. (##-##)** | **Year** | **ISBN** |
| | None | | | | | | | |

| | **Edited Volumes** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| D | **Full Author List** | **Edited Volume Title** | **Edition** | **Volume Number** | **Publisher** | | **Year** | **ISBN** |
| | None | | | | | | | |

| | **Conference Publications** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Full Author List** | **"Article Title"** | **Paper Number** | **Conference/Proceedings Title** | **Conference Location** | **Dates** | **CD Rom Volume or Volume, pp. (##-##)** | **ISBN** |
| | Mark E. Thompson | The Use of Organometallic Complexes to Squeeze Every Last Photon Out of Organic LEDs | N/A | Materials Research Society | Boston, MA | Nov. 26 , 2017 - Dec. 1, 2017 | N/A | N/A |
| | Abegail Tadle, Karim El Roz, Chan Ho Soh, Daniel Sylvinson M.R., Stephen R. Forrest, and Mark E. Thompson | Developing Blue Fluorescent Dopants for Organic Electronics | N/A | 2nd International Symposium on Soft Crystals | Chiba, Japan | July 12-14, 2019 | N/A | N/A |
| E | Abegail Tadle, Karim El Roz, Chan Ho Soh, Daniel Sylvinson M.R., Stephen R. Forrest, and Mark E. Thompson | Tuning the Optical and Photphysical Properties of Boron Aza-Dipyridylmethene Dyes for Optoelectronic Applications | N/A | Poster: 23rd International Symposium on the Photochemistry and Photophysics of Coordination Compounds (ISPPCC) | Hong Kong, China (SAR) | July 14-19, 2019 | N/A | N/A |
| | Muazzam Idris, Chan Ho So, Moon Chul Jung, Peter I. Djurovich, Stephen R. Forrest, and Mark E. Thompson | Tuning Singlet and Triplet Excited State Energies and Frontier Orbitals of Imidazole Host/Emitter for Hybrid White OLEDs | N/A | Poster: International Conference on Photochemistry | Boulder, CO | July 21-28, 2019 | N/A | N/A |
| | Stephen R. Forrest | Major Challenges Facing OLEDs for Displays and Lighting | N/A | International Conference on Plastic and Flexible Electronics (ICPFE 2017) | Jeju, Korea | Sept. 5, 2017 | N/A | N/A |
| | Stephen R. Forrest | Waiting for Act II: What is the future of Organic Electronics after OLED displays? | N/A | Nature Conference on Flexible Electronics (NDFE 2018) | Xi'an, China | Oct, 2018 | N/A | N/A |
| | Stephen R. Forrest | Waiting for Act II: What is the future of Organic Electronics after OLED displays? | N/A | International Conference on Electroluminescence (ICEL 2018) | Jeju, Korea | Oct, 2018 | N/A | N/A |

| | **Conference Presentations** | | | | | |
|---|---|---|---|---|---|---|
| | **Full Author List** | **"Paper Title"** | **Paper Number** | **Session/Symposium/Conference** | **Conference Location** | **Dates** |
| | Mark Thompson | Electrophosphorescence for Solid-State Lighting | Invited Speaker | OLED Stakeholders Workshop | Minneapolis, MN | October 10, 2017 |
| | Mark Thompson | The Use of Organometallic Complexes to Squeeze Every Last Photon Out of Organic LEDs | Invited Speaker | Materals Research Society Meeting | Boston, MA | November 29, 2017 |
| | Abegail Tadle, Karim El Roz, Chanho Soh, Daniel Sylvinson M.R., Stephen Forrest, Mark E. Thompson | Tuning the Optical and Photophysical Properties of Boron Aza-Dipyridylmethene dyes for Optoelectronic Applications | Poster Presentation (7/16/19) | 23rd International Symposium on the Photochemistry and Photophysics of Coordination Compounds (ISPPCC) | City University Hong Kong | July 14-19, 2019 |
| F | Mark E. Thompson | Modern Alchemy: Making Coinage Metals Look Like Iridum and Platinum | Plenary Speaker (7/16/19) | 23rd International Symposium on the Photochemistry and Photophysics of Coordination Compounds (ISPPCC) | City University Hong Kong | July 14-19, 2019 |

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|---|---|---|---|---|---|---|
| | Mark E. Thompson | Modern Alchemy: Making Coinage Metals Look Like Iridum and Platinum | Keynote Speaker | The 29th International Conference on Photochemistry (ICP) | University of Colorado, Boulder | July 21-28, 2019 |
| | Muazzam Idris, Chan Ho So, Moon Chul Jung, Abegail Tadle, Karim El Roz, Peter I. Djurovich, Stephen R. Forrest, Mark E. Thompson | Phenanthro[9,10-d]imidazole as Hosts and Fluorescent Emitters for Hybrid White Organic Light-emitting Diode Application | Poster Presentation | The 29th International Conference on Photochemistry (ICP) | University of Colorado, Boulder | July 21-28, 2019 |

| | Students Supported/Supervised/Graduated (University Awards Only) | | | | | |
|---|---|---|---|---|---|---|
| | **Name** | **BS/MS/PhD/Postdoc** | **From: (Semester-Year)** | **To: (Semester-Year)** | **Current Position, Affiliation** | **% Covered** |
| G | Muazzam Idris | PhD | Fall 2017 | Aug-19 | Graduate Student | 25% |
| | Karim El Roz | Postdoc | Fall 2017 | Apr-19 | Postdoctoral Research Asst | 100% |
| | Abegail Tadle | PhD | Fall 2017 | Aug-19 | Graduate Student | 50% |
| | Daniel Sylvinson Muthiah Ravinson | PhD | Spring 2018 | Aug-19 | Graduate Student | 25% |
| | Brenda Ontiveros | PhD | Fall 2018 | Aug-19 | Graduate Student | 50% |
| | Chanyeong Jeong | PhD | Fall 2017 | Nov-18 | Graduate Student | 50% |
| | Chan Ho Soh | PhD | Fall 2017 | Jun-19 | Graduate Student | 50% |
| | | | | | | |

| | Patent Applications Filed and Patents Awarded | | | | |
|---|---|---|---|---|---|
| | **Full Inventor List** | **"Patent Title"** | **Date Application Filed** | **Patent Application Number** | **Date Awarded (if applicable)** |
| H | Thompson, Mark E.; Idris, Muazzam; Tadle, Abegail; El Roz, Karim; Forrest, Stephen R.; Soh, Chanho | OLED WITH HYBRID EMISSIVE LAYER | 2/1/2018 | 62/623,764 / Provisional<br>(USC File No. 2018-134) (USPTO 16/262,408) | Licensed to UDC |
| | Forrest, Stephen R.; Soh, Chanho | ULTRA THIN DOPING FOR TRIPLET DIFFUSION EMISSION IN ORGANIC LIGHT EMITTING DEVICES | 2/7/2018 | (UM FILE NO # UM2018-282) | Licensed to UDC |
| | Thompson, Mark E.: Tadle, Abegail; Ravinson, Daniel Sylvinson Muthiah; Jung, Moon Chul; Idris, Muazzam; El Roz, Karim; Djuroivch, Peter; Soh, Chanho; Forrest, Stephen | FLUORESCENT DOPANTS AND HOSTS FOR HYBRID WHITE OLED | 1/18/2019 | 16/262,460 / Provisional<br>(USC File No. 2019-119) | Licensed to UDC |
| | Forrest, Stephen R.; Coburn, Caleb; Qu, Yue | METHOD OF SPACING EMISSION LAYER AND METAL CATHODE | 10/16/2017 | (UM FILE NO # UM7746) | Licensed to UDC |
| | Forrest, Stephen R.; Soh, Chanho; Thompson, Mark E.; Idris, Muazzam | GRADE EMISSION LAYER FOR REDUCED EFFICIENCY ROLL-OFF OF HYBRID WHITE ORGANIC LIGHT EMITTING DIODES | 1/29/2019 | (UM FILE NO # UM2019-257)<br>(USPTO 62/798,225) | Licensed to UDC |
| | Forrest, Stephen R.; Kim, Jongchan | STABLE BLUE ORGANIC LIGHT EMITTING DEVICES WITH HIGH THERMAL STABILITY UTILIZING A MIXED HOST OF HIGH GLASS TRANSITION TEMPERATURE MATERIALS | 10/10/2019 | (UM FILE NO 2020-151) | Licensed to UDC |
| | Thompson, Mark E.; Forrest, Stephen R. | TANDEM HYBRID-FL/PH OLED AND PHOLED FOR WHITE LIGHT EMISSION | Disclosure Filed # 11/26/19 | (USC FILE NO # D2020-0133) | Licensed to UDC |

| | Major Honors, Awards, and other Accomplishments | | | |
|---|---|---|---|---|
| | **Recipient** | **Award** | **Sponsor** | **Date of Award** |
| | Abegail Tadle | Chemical Sciences Outstanding Poster Presentation | ISPPCC 2019 / Royal Society of Chemistry | July 14-19, 2019 |
| | Abegail Tadle | Best Poster Award | ISPPCC 2019 | July 14-19, 2019 |
| I | Muazzam Idris | Sustainable Energy & Fuels Poster Prize | 29th International Conference on Photochemistry | July 21-26, 2019 |
| | Stephen Forrest | Honorary PhD | The Technion, Israel Institute of Technology | 2018 |
| | Stephen Forrest | Elected Fellow | American Academy of Arts and Sciences | 2018 |
| | Stephen Forrest | Henry Russell Lectureship | University of Michigan | 2019 |

| | Private Funding (e.g. Venture Capital, Private Equity, etc.) leveraged by DOE Investment | | |
|---|---|---|---|
| | **Private Capital Partner** | **Amount of Funding** | **Date** |
| J | None | | |
| | | | |
| | | | |

**P.I.** **Likely not applicable for LPDP awards**

**CPS ID #:** **Likely not applicable for LPDP awards**

# VI. Subcontracts (for entire Project Period)

| No | Name | Work Description | Phase | Task | Funding |
|---|---|---|---|---|---|
| **1** | **University of Michigan** | Blue fl dopants with ∆EST <0.4 eV> |  | 1.3 | $102,420 |
| **2** | **University of Michigan** | Study of hybrid WOLEDs |  | 3 | $200,807 |
| **3** | **University of Michigan** | Device lifetime measurement (M4-M24) |  | 4 | $196,774 |
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|  |  |  |  |  | $500,001 |