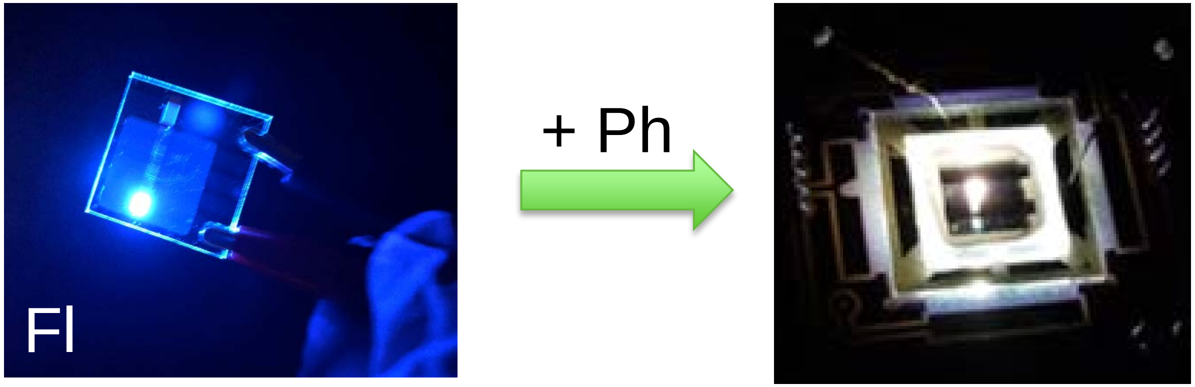
Combining Fluorescence and Phosphorescence to Achieve Very Long Lifetime and Efficient White OLEDs



University of Southern California and University of Michigan

PI: Mark Thompson, Professor of Chemistry

Email: met@usc.edu

Project Summary

Timeline:

Start date: October 1, 2017

Planned end date: September 30, 2019

Key Milestones

1. Milestone 1.1 – 1.4: Multiple blue fl-dopants, blue OLED EQE > 5% (Q1, Q2, Q3, Q4, Q6, Q7)
2. Milestone 2.1-2.2: Host materials for WOLED (Q2, Q4, Q6)
3. Milestone 3.1-3.3: Develop fl/ph hybrid WOLED, > 45 lm/W, CRI > 90 at 10k lm/m^2 (Q3, Q4, Q7)
4. Milestone 4.1-4.6: WOLED lifetime testing, goal L_{70} > 25k hours at 5k lm/m^2 (Q2-Q8)

Key Partners:

University of Michigan, Ann Arbor, MI	Universal Display Corp., Ewing, NJ

Budget:

Total Project $ to Date:

- DOE: $88,503
- Cost Share: $40,933

Total Project $:

- DOE: $801,092
- Cost Share: $225,309

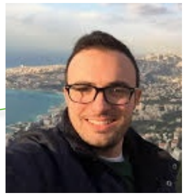
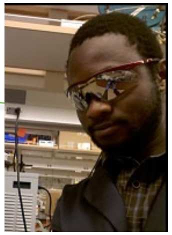
Project Outcome:

We are focused on developing a new white OLED (WOLED) structure and materials to realize it. This WOLED will be highly efficient and long lived, with adjustable color coordinates (soft to hard white). We are in the middle of the materials discovery effort and have begun to examine structures and new materials.

Team

- **University of Southern California**
  - PI: **Mark Thompson**
  - **Daniel Sylvinson:** Molecular Modeling (3rd Yr grad.)
  - **Abegail Tadle:** Emitter synthesis (3rd Yr grad.)
  - **Dr. Karim El Roz:** Emitter photophysics, blue OLED (Postdoc)
  - **Muazzam Idris:** Host synth, WOLED/OLED studies (4th Yr grad.)



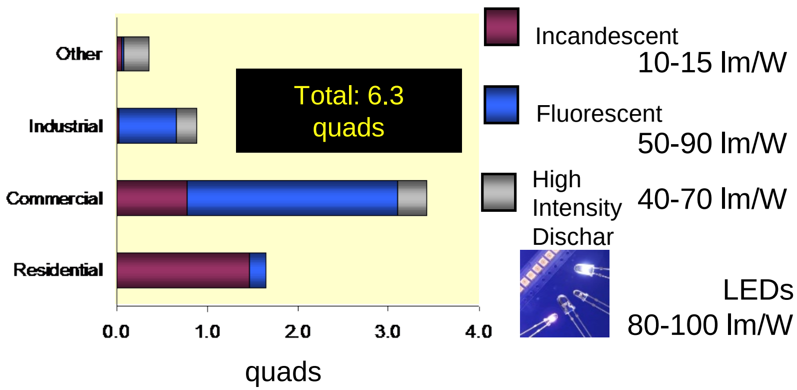



- **University of Michigan**
  - coPI: **Stephen Forrest**
  - **Chan Ho Soh:** WOLED/OLED and lifetime studies (1st Yr, grad.)
  - **Chanyeong Jeong:** WOLED/OLED studies (3rd Yr grad.)
  - *To be hired*: Postdoc

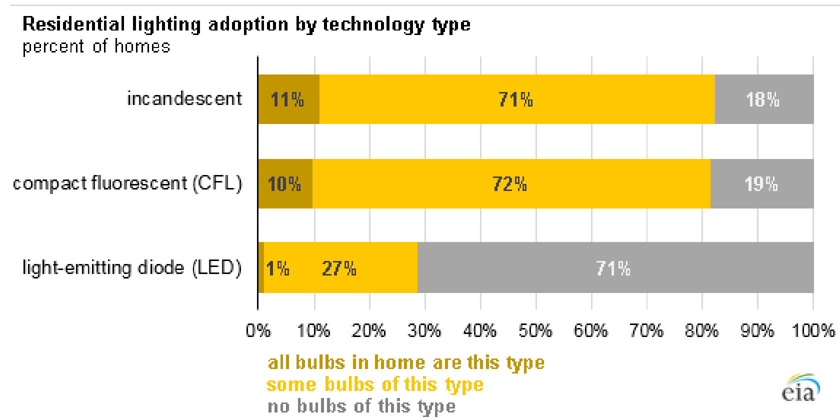


- ***Both teams have extensive experience with materials discovery and organic LEDs (Thompson/Forrest > 25 years)***

Challenge



BTS Core Databook, August 2002 [1]



2015 Residential Energy Consumption Survey[2]

- **Low efficiency lighting is common, consumes ~ 2 Quads**
- **Efficiencies are bulb eff., not luminaire efficiency**
- **LED is an efficient technology, but adoption is slow**
  - In 2015, nationwide, only 18% of households had no incandescent bulbs in their homes
  - Not as attractive at other lights
  - More expensive (not if considered over time)
- **OLED is a good alternative, but it needs: higher efficiency, longer lifetime, lower cost**

OLED SSL

Impact

- **DOE SSL 2020 OLED Core program goals:**[3]

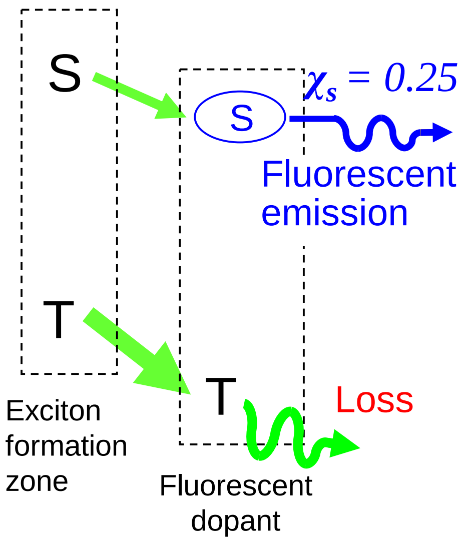
Metrics	2015 Status	2020 Target	2025 Target
Efficacy without extraction enhancement (lm/W)	35 lm/W	50 lm/W	60 lm/W
Color rendering index (CRI)	90	>90	>90
Lumen maintenance (L_{70}) from 10,000 lm/m^2	40,000	>50,000 hrs	>50,000 hrs

- **Our new fl/ph Hybrid WOLED offers:**
  - Higher efficiency $\Rightarrow$ lower power consumption
  - Multiple emitters $\Rightarrow$ tunable CCT at high CRI in a single OLED
  - High efficiency $\Rightarrow$ low power per lm $\Rightarrow$ longer lifetime
- **To accomplish this we need new materials and structures.**

Approach - 1

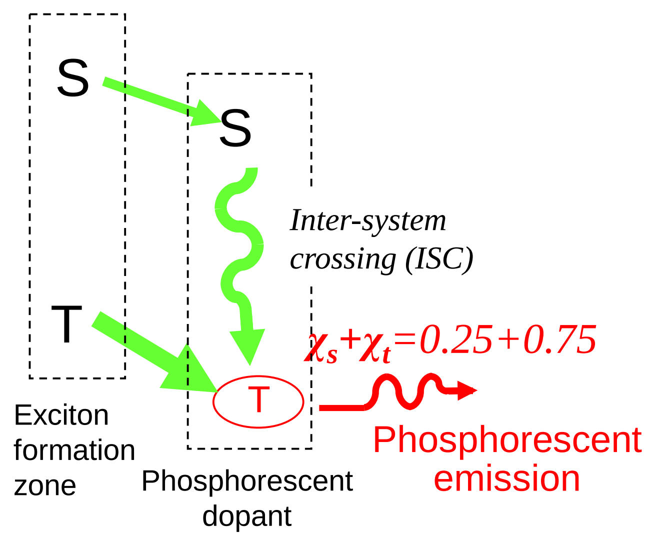
- ⊕/⊖ recombination gives singlet + triplet in 1:3 ratio

Fluorescence ONLY



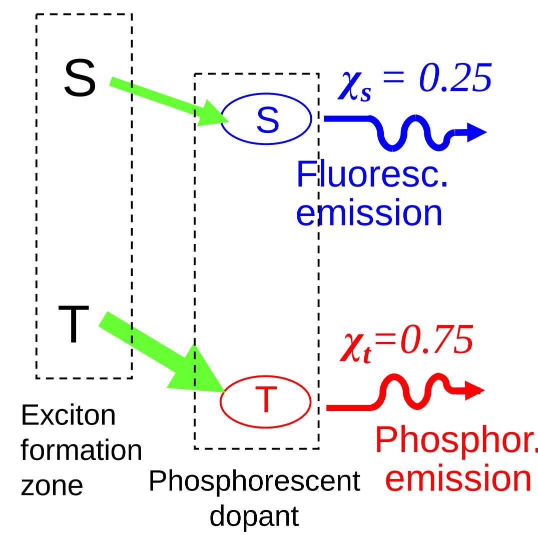
Color tuned by dopant
Problem:
Eff. Limit = 25%

Phosphorescence ONLY



Wide use in mobile displays
Color tuned by dopant
R/G lifetimes > 400K hours
Multiple dopant for white
No eff. Limit (100%)
Problems:
- Blue ph. give poor lifetime
- S→T energy loss limits lm/W

Fluorescence + Phosphorescence



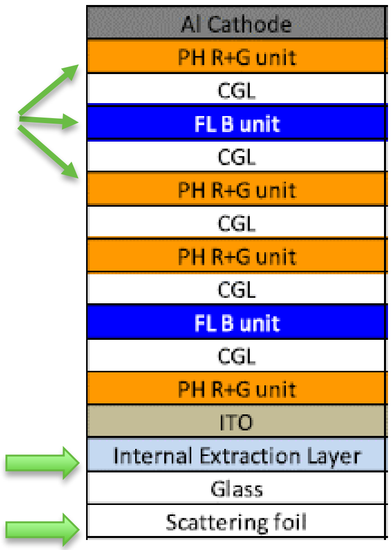
Color tuned by dopant
Multiple dopant for white
No eff. Limit (100%)
Blue fl-dopant:100K lifetime
Stable color balance
Relatively simple structure
Problems:
Need study/improvement

Approach - 2

- S/T separation can involve separate devices or a single given device

OLEDWorks Bright-2 [4]

(each OLED is 5-7 separate layers)

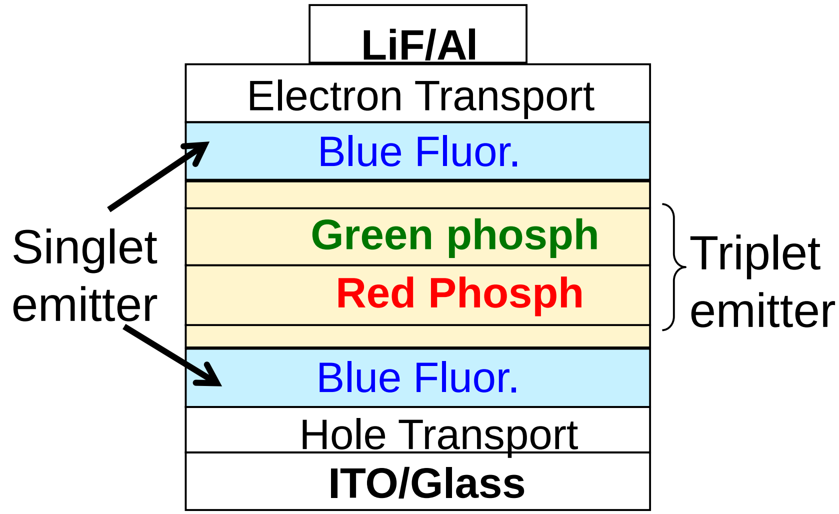


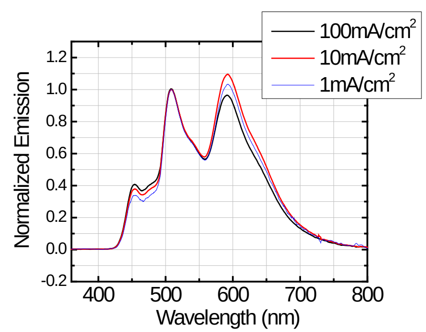
CCT: 3000K
CRI: 90
Eff.: 63 lm/W*
L_{70}: 50K hr.**

* Significant light extraction
** low brightness per OLED

Problem: very complicated structure

Hybrid WOLED [5]





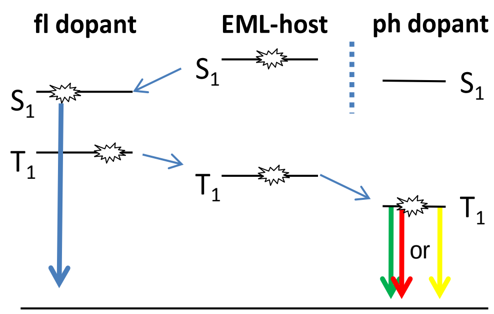
CCT: 3750K
CRI: 85
Eff.: 24 lm/W*
L_{70}: ?

* No light extraction, related WOLED > 40 lm/W [7]

Problem: poor fl-dopant and matrix choice in previous studies

Progress - Overview

- **Program start date:** October 1, 2017, we are at an early stage
- Needed for hybrid-WOLED:
  - fl-dopants
  - hosts tailored to fl-dopants
  - device structures
  - lifetime testing



- Materials and device design/testing by a staged approach

Modeling ⇄ Synthesis, characterizaiton ⇄ Blue and hybrid White OLED test ⇄ Blue and WOLED lifetime test

- USC: modeling, synthesis/characterization, blue OLED
- UM: blue OLED, hybrid-WOLED, lifetime testing

Progress – Plan and Milestones

Plan:

- fl-dopant and host developed in parallel
    - New materials transferred to UM quickly
- WOLED studies began with known mats.
- Lifetime testing of known hybrid-WOLEDs

Milestones completed for Q1 and Q2

1.1: Model > 300 fl-dopants ⇒ database

1.2.1: Prepare and characterize 2 fl-dopants from 1.1

2.1: Model > 200 hosts ⇒ database

4.1: Lifetimes of known hybrid WOLEDs

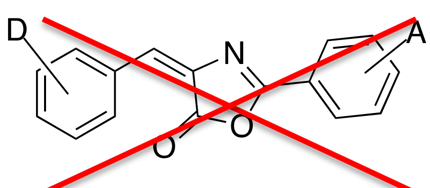
<u>All accomplished on-time or ahead</u>

Task-Milestone	Q 1	Q 2	Q 3	Q 4	Q 5	Q 6	Q 7	Q 8
Project Management								
Task 1: blue fl-dopant								
Milestone 1.1	→							
Milestone 1.2.1		→						
Milestone 1.2.2			→					
Milestone 1.3				→				
Milestone 1.4.1						→		
Milestone 1.4.2							→	
Task 2: fl/ph host mater.								
Milestone 2.1		→						
Milestone 2.2.1				→				
Milestone 2.2.2					→			
Task 3: fl/ph WOLEDs								
Milestone 3.1			→					
Milestone 3.2				→				
Milestone 3.3							→	
Task 4: Lifetime testing								
Milestone 4.1		→						
Milestone 4.2			→					
Milestone 4.3.1				→				
Milestone 4.3.2					→			
Milestone 4.4						→		
Milestone 4.5							→	
Milestone 4.6								→
Go/NoGo Milestone				→				
Final Milestone								→
Deliverables: reports	→	→	→	→	→	→	→	→
Technology Transfer								

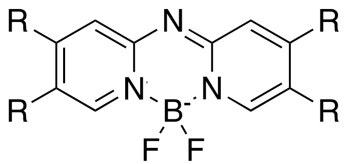
Progress – Modeling and fl-dopant selection

- **Requirements for blue emitters:**
  - Small singlet-triplet energy gap (ΔE_{ST} < 0.4 eV).
  - T_1 of the fl-emitter needs to be > 2.5 eV
  - High fluoresce. quantum yield (> 70 %) at 450 nm (2.76 eV)
- **Density Functional Theory (B3LYP, 631G** Basis set)**

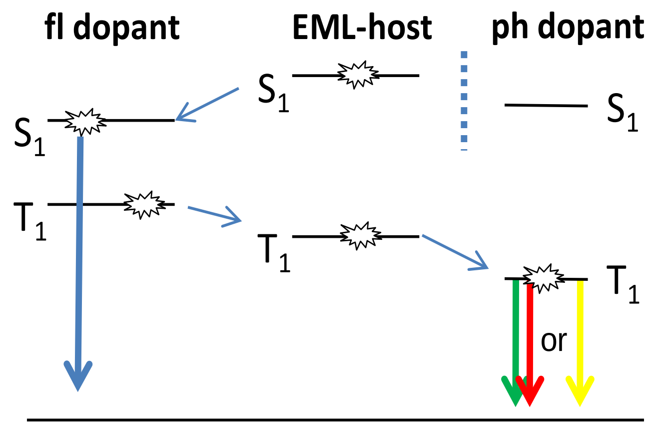
<u>fl-dopant candidates *(ca. > 300 structures):*</u>



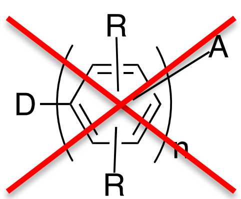
Oxazolone core
"Jelly Fish"



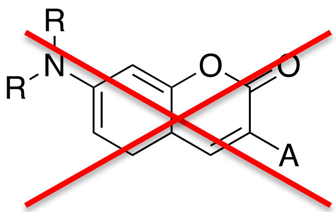
B-aza-DiPYR



ΔE_{ST} > 0.8

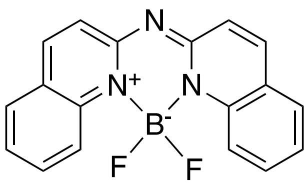


oligophenylene

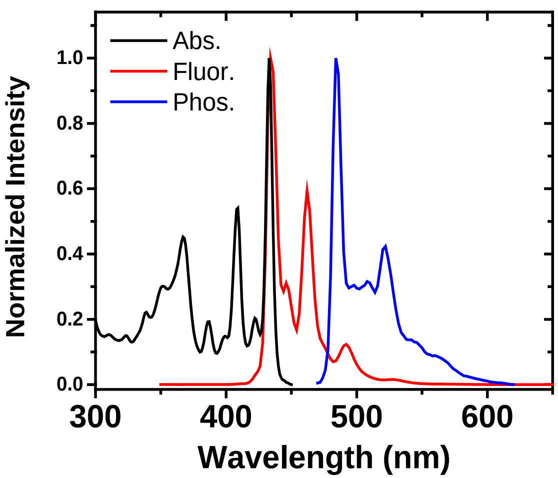


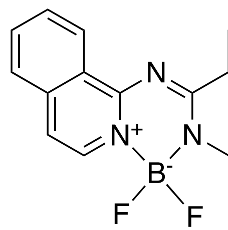
Coumarin

Progress –fl-dopant properties

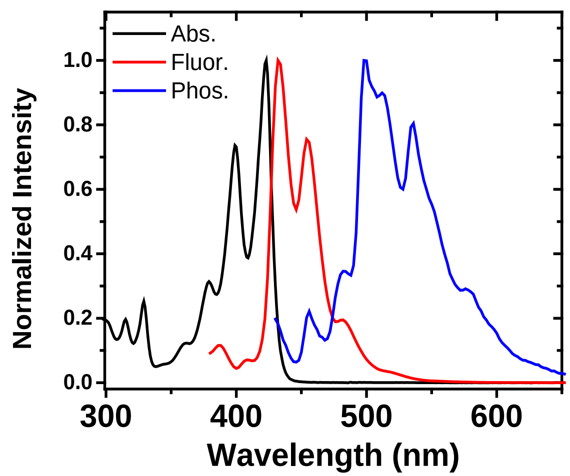


α-azaDiPYR





γ-azaDIPYR

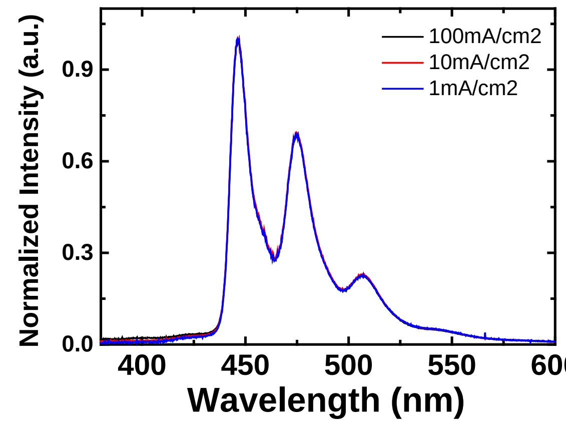


	Calc. (eV)	Expt. (eV)
S_1	2.78	2.86 (434 nm)
T_1	2.39	2.56 (484 nm)
ΔE_{ST}	0.39	0.30
Φ_{fl}	Solution	0.86
Φ_{fl}	PMMA	0.86

	Calc. (eV)	Expt. (eV)
S_1	2.78	2.87 (432 nm)
T_1	2.39	2.57 (482 nm)
ΔE_{ST}	0.39	0.30
Φ_{fl}	Solution	0.87
Φ_{fl}	PMMA	0.90

Blue-OLED

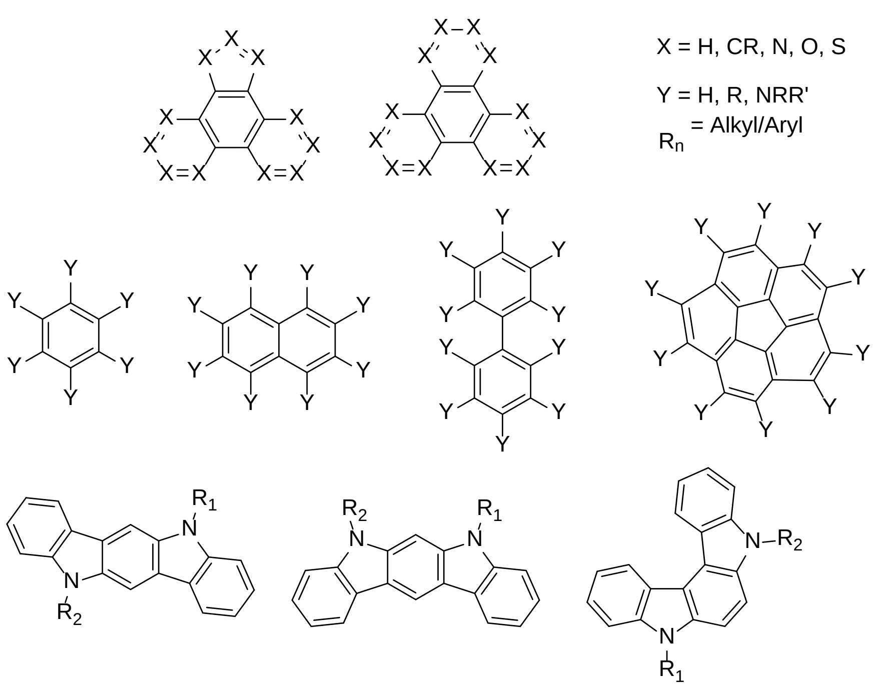
α-azaDIPYR

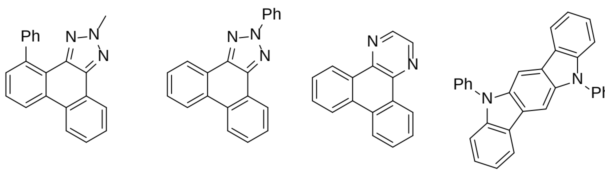


- Host = carbazole-biphenyl (CBP)
- λ_{max} = 450 nm
- Turn on ~ 3V
- Peak EQE 4.5% (Singlet only theoretical maximum = 5.5%)
- Hybrid WOLED studies in progress

Progress – Host materials

- **Computational screening used for host materials.**
  - Large singlet-triplet energy gap, ΔE_{ST} > 0.8 eV
    (dopant must be nested within the host HOMO/LUMO levels)
  - T_1 of the fl-emitter needs to be 2.7-2.7 eV in the solid state (0.1-0.2 eV red shift in solid compared to model)
- **Modeling of > 200 candidate materials:**

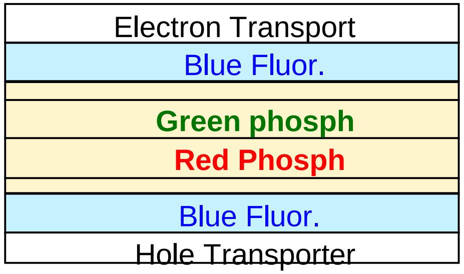


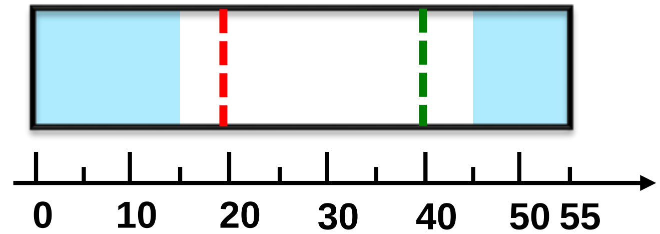


1 2 3 4

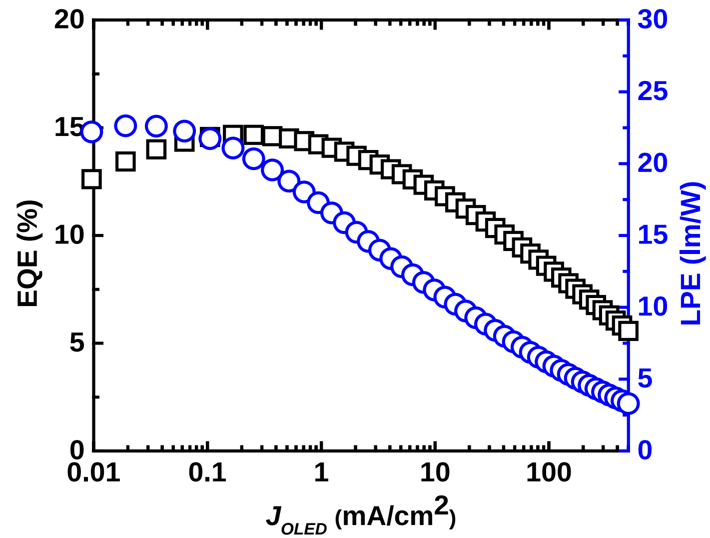
	S_1 (eV)	T_1 - Solution (eV)	ΔE_{ST}
1	3.65	2.70	0.95
2	3.51	2.76	0.75
3	3.35	2.84	0.51
4	3.28	2.70	0.58

Progress – Hybrid WOLED study

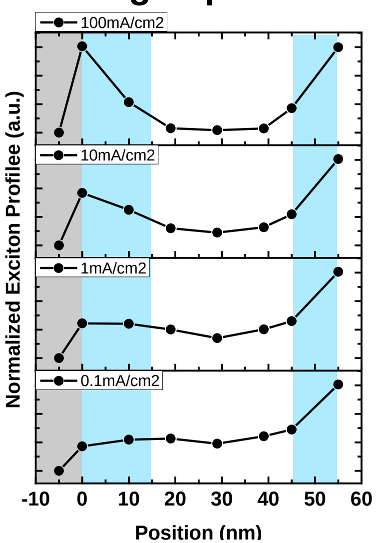




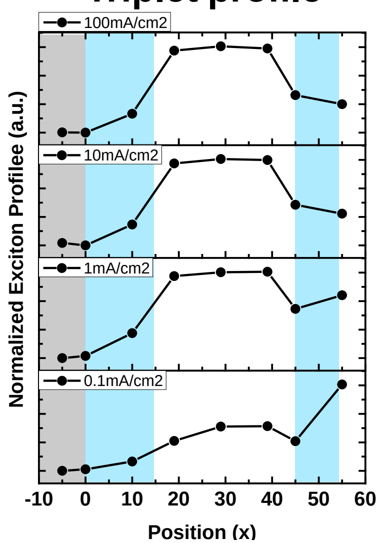
- Exciton profile by delta doping: 0.5Å slab of red lumophores at position[6]
- Exciton formed at EML edge (0-15nm)
- Suggests narrow ph-dopant profile



Singlet profile



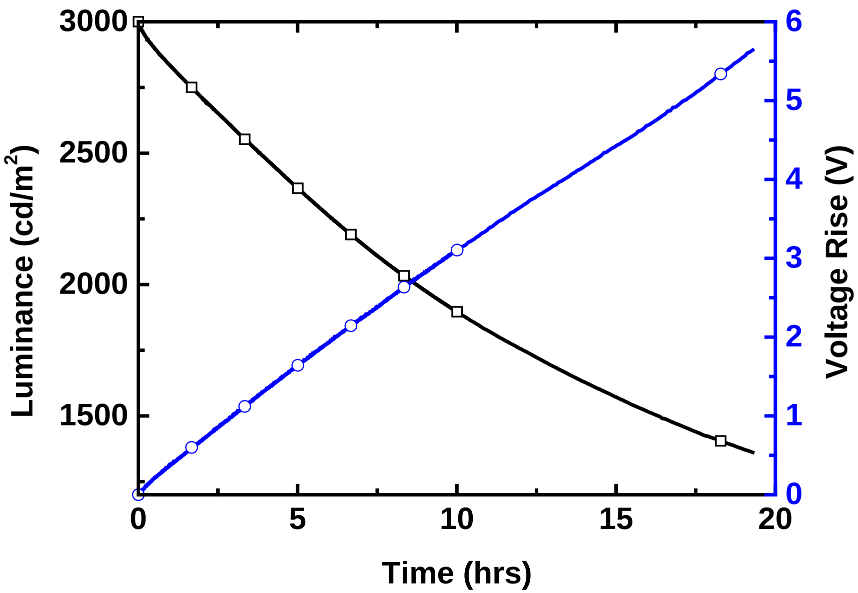
Triplet profile



- Delta doped layers of phosphors (< 1nm)
- Other layers identical to original device (poor blue dopant and host)
- CRI = 84, CIE = (0.45 0.4) @ 100mA/cm^2
- Peak EQE of 14.5% (up from 11.3%)
  - ❖ Phosphor charge trapping minimized

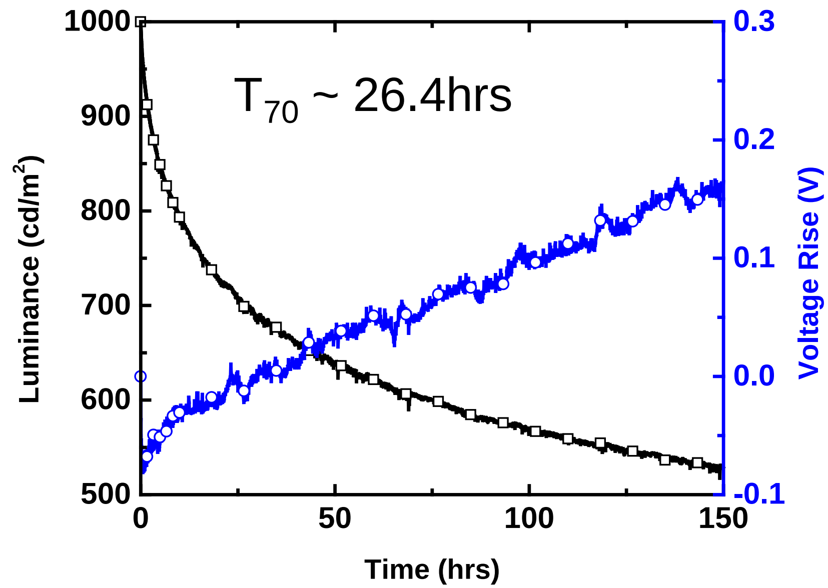
Progress – Lifetime

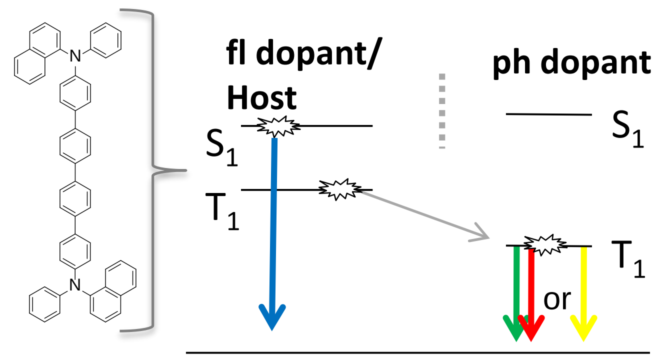
Previously published hybrid-WOLED [5]



- Forward viewing EQE of 11.5%
- CRI = 88, CIE = (0.44 0.42) @ 100mA/cm^2
- Short lifetime (T_{70} = 4hrs at 3000nits)
  - ❖ Exciton build-up at the sharp interface
  - ❖ Unstable blue dopant and host (CBP)

fl/ph hybrid-WOLED with a fluorescent host (no dopant) [7]





- Details of lifetime to be studied

Remaining Project Work

- **Immediate Future:**
  - Test aza-DIPYR dyes in OLEDs with new host matrices
  - Incorporate aza-DIPYR dyes into fl/ph hybrid WOLEDs
  - Test lifetimes of hybrid WOLEDs with “soft” interfaces
  - Test lifetimes of hybrid WOLEDs with delta doped phosphors
- **Next step:**
  - Optimize fl/ph hybrid WOLED with new dopants and hosts
  - Test lifetimes of optimized fl/ph hybrid WOLEDs
  - Prepare and test aza-DIPYR dyes with solubilizing groups
  - Prepare and test Coumarin and aza-DIPYR dyes as fluorescent host materials, simplified WOLED structure

Stakeholder Engagement

- **Early stage program**
- **Close relationship with Universal Display Corp.**
  - UDC commercialized phosphorescent dopants that are in > 1.5 billion cell phone (Samsung Galaxy)
    - The majority of their materials are manufactured in the US
  - Fully developed technology transfer avenues between USC/UM and UDC
  - UDC is interested in commercializing WOLED for SSL, color sector lighting, display backlights

UNIVERSAL DISPLAY CORPORATION™

Thank You

University of Southern California and University of Michigan

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3. Solid-State Lighting 2017 Suggested Research Topics: https://www.energy.gov/sites/prod/files/2017/09/f37/ssl_suggested-research-topics_sep2017.pdf
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6. Lee, J., Jeong, C., Batagoda, T., Coburn, C., Thompson, M. and Forrest, S., “Hot excited state management for long-lived blue phosphorescent organic light-emitting diodes.” *Nature Comm.*, **2017**, *8*, 15566
7. Schwartz, G.; Reineke, S.; Rosenow, T. C.; Walzer, K.; Leo, K., Triplet Harvesting in Hybrid White Organic Light-Emitting Diodes. *Adv. Func. Mater.* **2009**, *19*, 1319.

Project Budget

Project Budget: Two year program (10/2017-9/2019). 50/50 split USC/UM

Variances: Underspent our budget to date. Reasons: (1) equipment ordered, but not yet delivered, (2) funds for summer salaries not expensed yet, (3) Postdoc at UM not hired yet, (4) multiple students received fellowship/TA support, so DOE funds were not needed to fully support them (yet).

Cost to Date: Q1 & Q2 DOE Spent = $88,503 / Cost-Share = $40,933

Starting Q3 – April 2018 Estimated Expenditures:

DOE = $49,956 / Cost-Share = $8,110

Additional Funding: Partial support for the research from Universal Display Co.

Budget History					
FY 2017 (N/A) (past)		FY 2018 (current)		FY 2019 – 09/30/19 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	$401,092	$111,646	$400,000	$113,663

Project Plan and Schedule

Project plan											
Initiation date: Oct. 1, 2017; planned completion date: Sept. 30, 2019											
◆ : Milestone Planned or Projected (all milestones finished on time to date)											
BLUE: completed task; GREEN: Task in progress; ⟶ : Task to be started later											
Task #	Type	Milestone #	Milestone Description	------FY 2018------				------FY 2019------			
				Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
1.1	dopant	1.1	Model fl dopants	◆							
1.2	dopant	1.2.1	Prepare 2 fl dopants		◆						
2.1	host	2.1	Model fl/ph WOLED hosts		◆						
4	lifetime	4.1	Lifetime: published fl/ph WOLED		◆						
1.2	dopant	1.2.1	Prepare 4 fl dopants			◆					
3	fl/ph WOLED	3.1	WOLED with fl dopant from Task 1			◆					
1.3	dopant	1.3	Prepare & test blue OLEDs				◆				
4	lifetime	4.2	Lifetime of OLEDs in Task 1.3				◆				
2.2	host	2.2.1	Prepare hole transport hosts				◆				
3	Fl/ph WOLED	3.2	Dopant from 3.1 + host from Task 2				◆				
4	lifetime	4.3.1	Lifetime of OLEDs in Task 1.4.1				⟶ ◆				
	Go/NoGo		Performance of hybrid fl/ph WOLED				◆				
2.2	WOLED host	2.2.2	Prepare e^- transport hosts				⟶	◆			
4	lifetime	4.3.2	Lifetime of OLEDs in Task 1.4.2				⟶	◆			
1.4	dopant	1.4.1	Blue OLEDs in h^+ WOLED host					⟶	◆		
4	lifetime	4.4	Lifetime of WOLEDs in Task 4.1					⟶	◆		
1.4	dopant	1.4.2	Blue OLEDs in e^- WOLED host					⟶	⟶	◆	
3	Fl/ph WOLED	3.3	3.2 + optimized ph dopants						⟶	◆	
4	lifetime	4.5	Lifetime of OLEDs in Task 4.2							⟶ ◆	
4	lifetime	4.6	Lifetime of OLEDs in Task 4.3							⟶	◆
		Final	Performance of hybrid fl/ph WOLED								◆

- Go/No-Go Metric (End of Year 1): Hybrid fl/ph WOLED: > 40 lm/W and a CRI > 80.
- Final Metric: Hybrid fl/ph WOLED: > 50 lm/W, CRI > 90, L_{70} > 25K hrs at 5k lm/m^2