# The Path for OLEDs in Lighting

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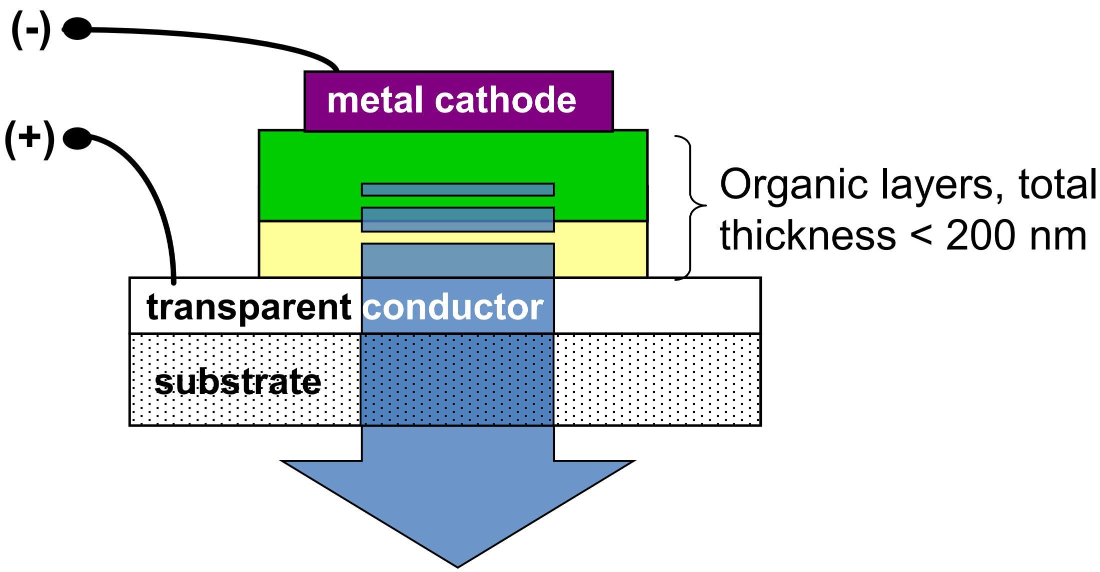
# OLEDs and Their Benefits




- Can be prepared on any substrate - active materials are amorphous
- Low cost materials and fabrication methods, scalable to large area
- Readily tuned color and electronic properties *via* Chemistry
- Can be transparent when off
- Device characteristics
  - Efficiency ~ 100% demonstrated, white > 120 lm/W
  - > 1,000,000 hour (10 years) lifetime
  - Can be very bright: $10^6$ cd/m$^2$, CRT = 100 cd/m$^2$, fluorescent panel = 800 cd/m$^2$
  - Turn-on voltages as low as 3 Volts

# 100% Internal Efficiency via Spin-Orbit Coupling

## Heavy metal induced electrophosphorescence ~100% QE

Baldo, Thompson, Forrest, et al., Nature **395**, 151 (1998)

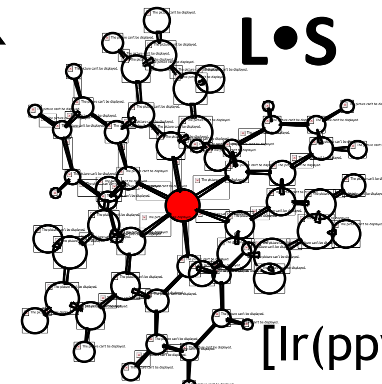
**MOLECULAR EXCITED STATES AFTER ELECTRICAL EXCITATION**

25% 75% 100%

**Singlet**
*spin anti-symmetric*

**Triplet**
*spin symmetric*

**L•S**



[Ir(ppy)$_3$]

**Phosphorescence enhanced by mixing S+T** eg: spin-orbit coupling via heavy metal atom

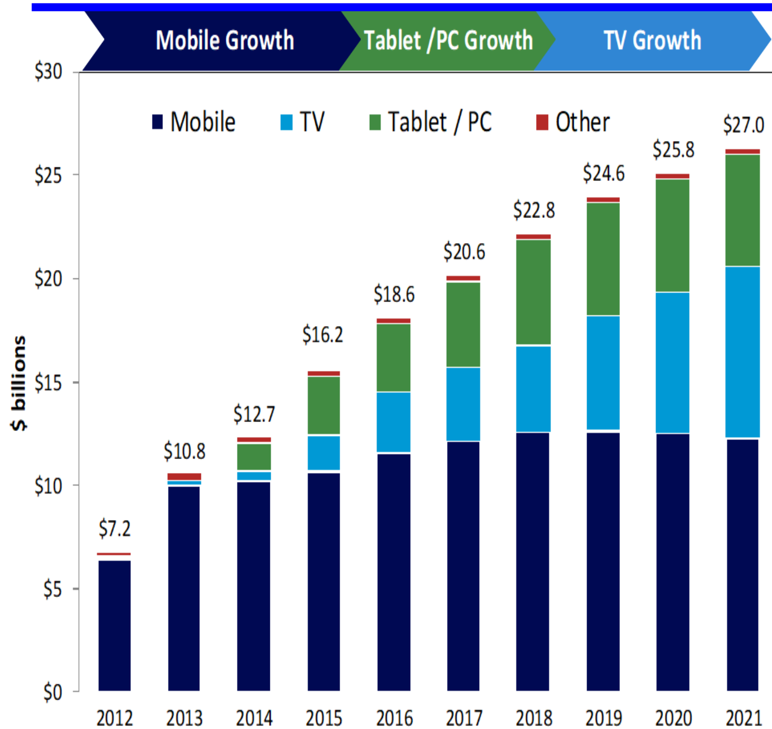
Relaxation allowed
fast, efficient
'Fluorescence'

Relaxation disallowed
slow, inefficient
'Phosphorescence'

Relaxation allowed
not so slow, efficient
'Phosphorescence'

**GROUND STATE**
*spin anti-symmetric*

# AMOLED Displays: Driving the Technology




*Source: DisplaySearch, Q2'14*



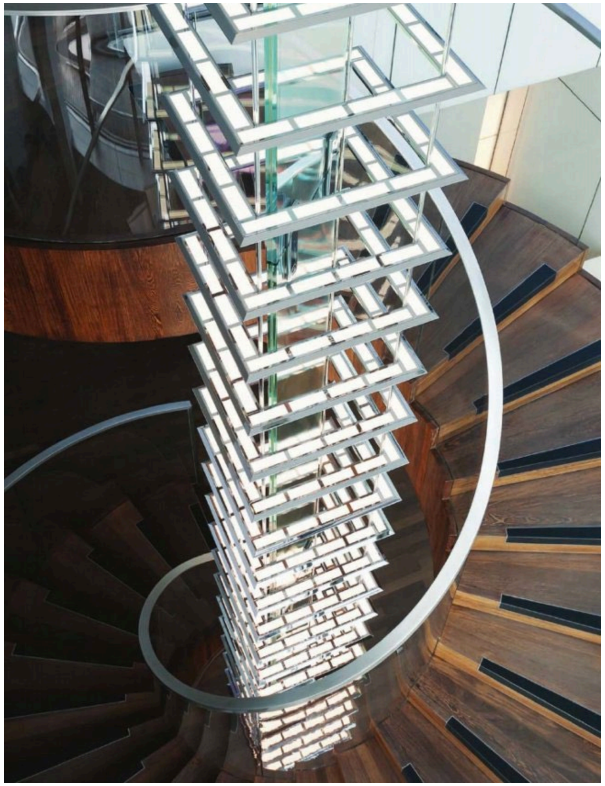
2010: Galaxy Phones
Phosphorescent R,G
>2 Billion sold!

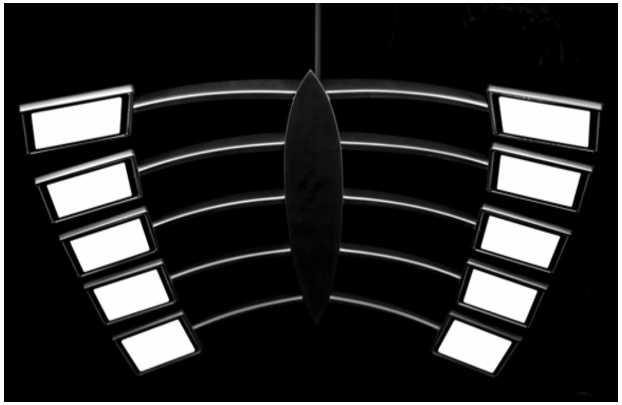
2012: LG 55" & Samsung
Phosphorescent TV, $1500
2017: iPhone 8?

2014-15: 65" and 77" OLED TVs
2016: 4K OLED TV

Panasonic, Sony, Toshiba....(2017)

# White Light is Rapidly Becoming a Reality...





# Lighting Comparison

| | Incandescent | Fluorescent | LEDs | OLEDs |
|---|---|---|---|---|
| **Efficacy** | 17 lm/W | 100 lm/W | 80-90 lm/W – White<br>65 lm/W – warm white<br>240 lm/W-lab demo | **150 lm/W<br>Lab demos** |
| **CRI** | 100 | 80-85 | 80 – white<br>90 – warm white | **Up to 95** |
| **Form Factor** | Heat generating | Long or compact gas filled glass tube | Point source high intensity lamp | **Large area thin diffuse source. Flexible, transparent** |
| **Safety concerns** | Very hot | Contains mercury | Very hot in operation | **None to date** |
| **LT70 (K hours)** | 1 | 20 | 50 | **30** |
| **Dimmable** | Yes, but much lower efficacy | Yes, efficiency decreases | Yes, efficiency increases | **Yes, efficiency increases** |
| **Noise** | No | Yes | No | **No** |
| **Switching lifetime** | Poor | Poor | Excellent | **Excellent** |
| **Color Tunable** | No | No | Yes | **Yes** |

# OLEDs: Major Challenges for Lighting

- Big picture issues
  - The importance of materials: small molecule vs. polymer
  - The importance of purity (see above)
- Getting the Light Out
- Blue Lifetime
- Cost & Yield
  - Patterning & Deposition
  - Throughput

# Current Status of OLED Lifetime

## Commercial OLED performance (2016)

| Color | CIE | LE (cd/A) | $t_{50}$ (hrs) |
|---|---|---|---|
| Red | [0.64, 0.36] | 30 | 900,000 |
| Green | [0.31, 0.63] | 85 | 400,000 |
| Blue | ? | ? | <100 |

Phosphorescent OLED dopants

| Color | CIE | LE (cd/A) | $t_{50}$ (hrs) |
|---|---|---|---|
| Red | [0.67, 0.33] | 11 | 160,000 |
| Green | [0.31, 0.63] | 37 | 200,000 |
| Blue | [0.14, 0.12] | 9.9 | 11,000 |

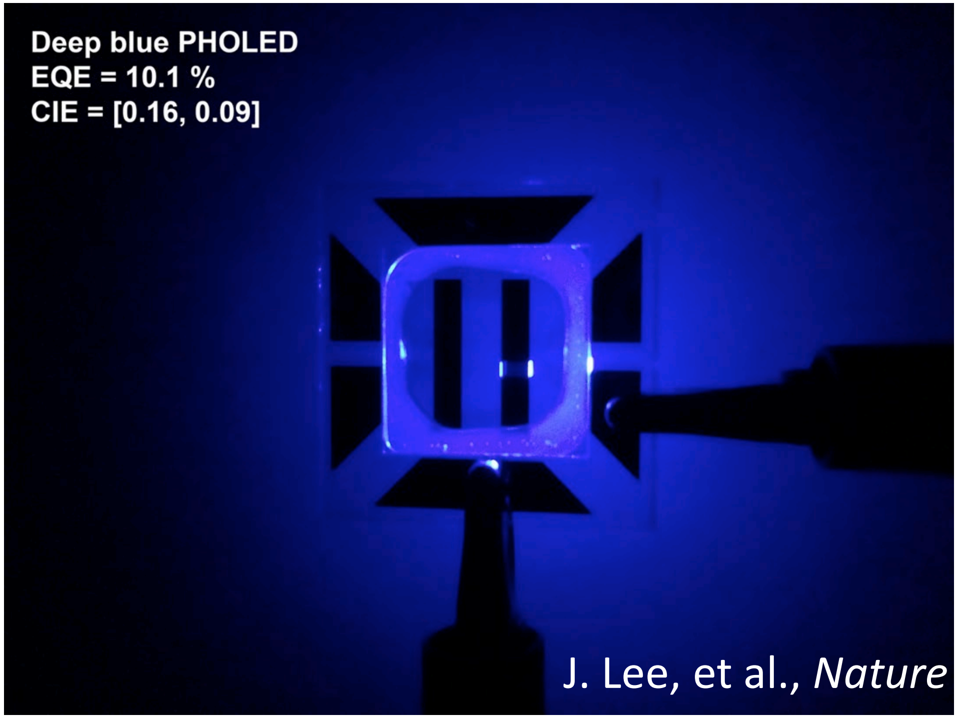
Fluorescent OLED dopants

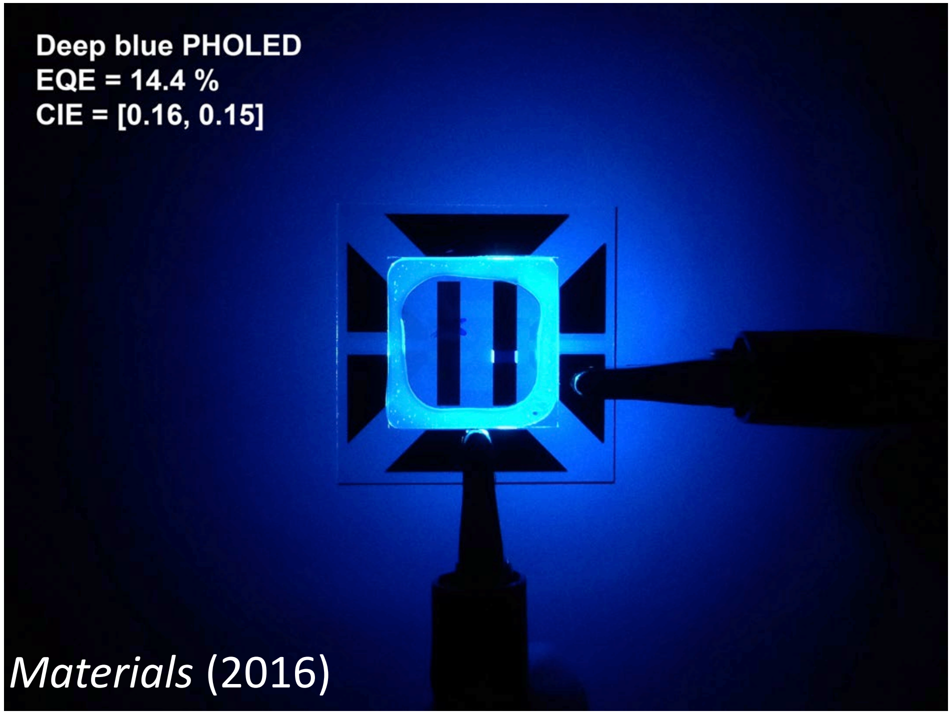
**Long lived blue PHOLED: A high value problem!**

| | |
|---|---|
| **Red** PHOLED: | Reduces power 25% |
| + **Green** PHOLED: | Reduces power 45% |
| + **Blue** PHOLED: | Reduces power 74% |

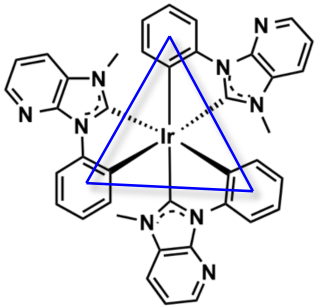
# Blue is Beautiful

## Very high intensity, efficient deep blue PHOLEDs

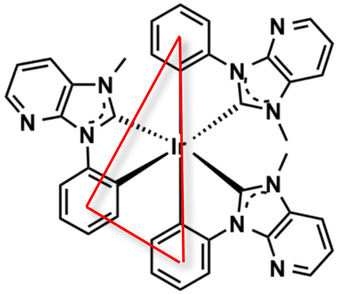



J. Lee, et al., *Nature Materials* (2016)



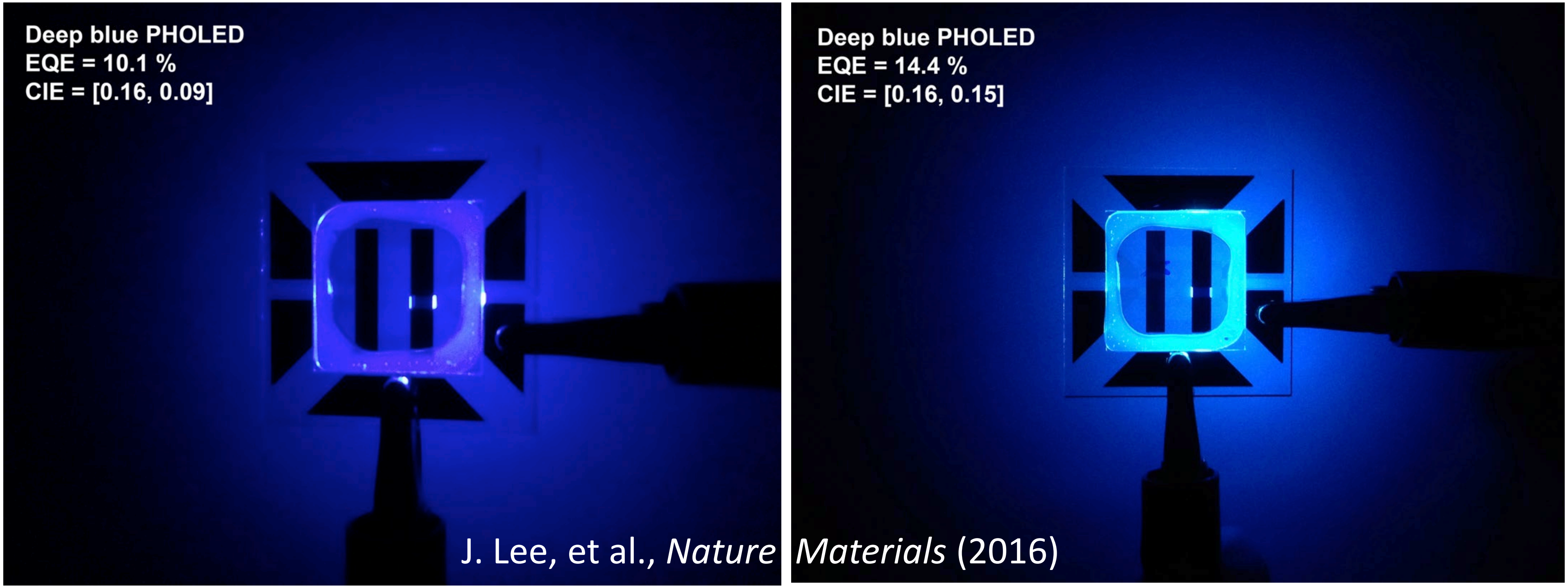
***fac***-Ir(***pmP***)$_3$



***mer***-Ir(***pmP***)$_3$

# Blue is Beautiful

Very high intensity, efficient deep blue PHOLEDs

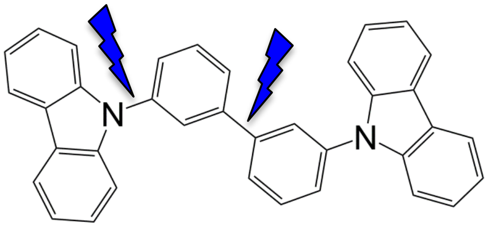



J. Lee, et al., *Nature Materials* (2016)

# ….but short lived

# Molecular Degradation Is Energy Driven

- Lifetime of OLEDs: R>G>B
- Implication: Device death is energy driven




| Bond | BE(eV) | Bond | BE(eV) |
|---|---|---|---|
| C-C | 3.64 | N-N | 1.69 |
| C-H | 4.28 | N-O | 2.08 |
| C-O | 3.71 | N-H | 4.05 |
| C-N | 3.04 | O-O | 1.51 |
| C-F | 5.03 | H-H | 4.52 |

**Bond cleavage**
Broken bonds → Defects!

**Energy Scale**

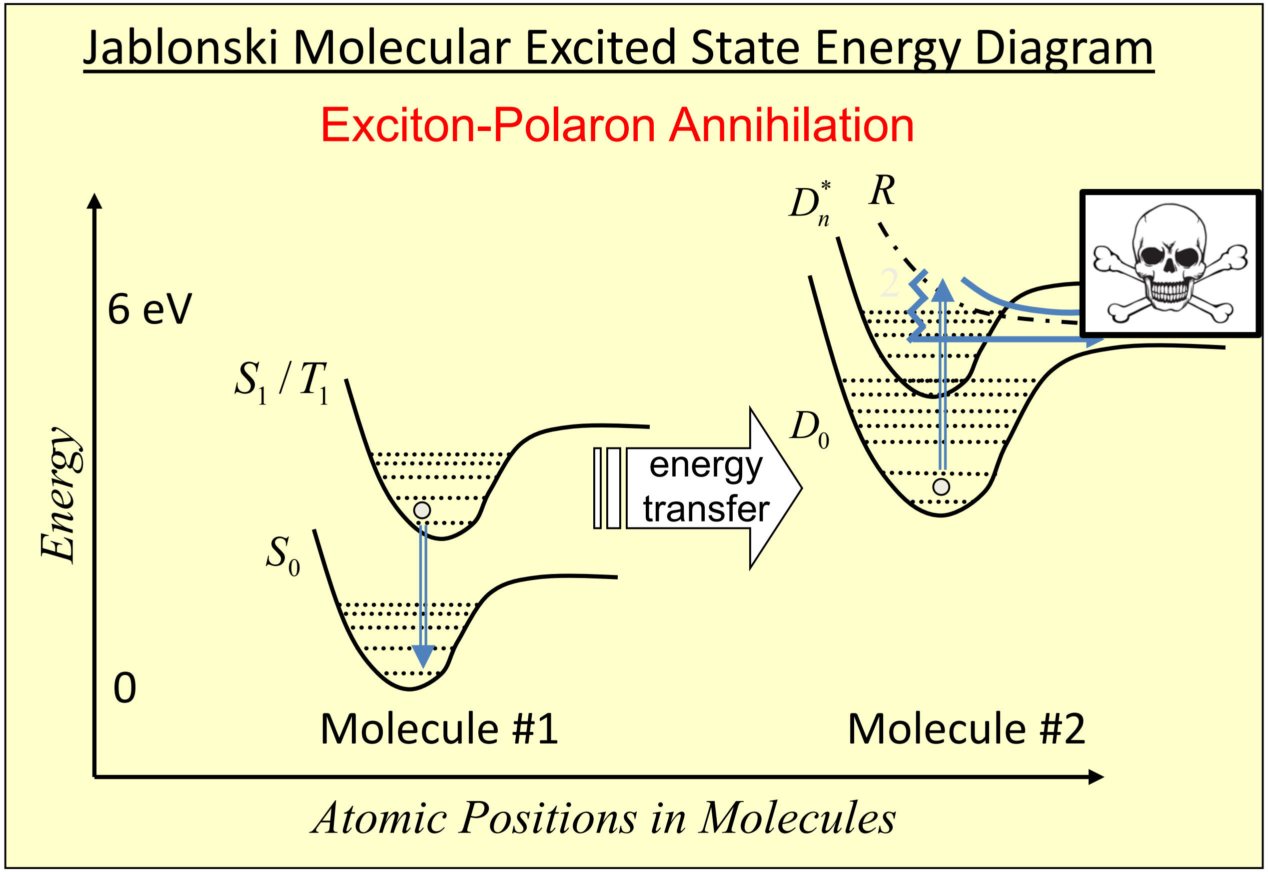
**Red light: ~ 2 eV**

**Green light: ~2.3 eV**

**Blue light: ~ 2.9 eV**

**But there doesn’t seem to be enough energy to destroy the molecules….Or is there?**

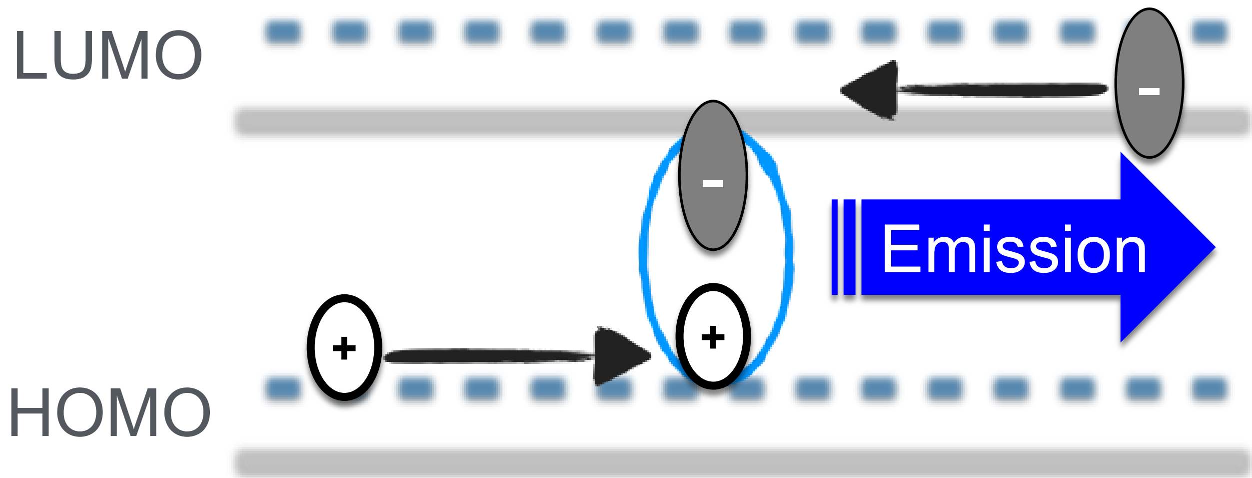
# When Excited States Collide…

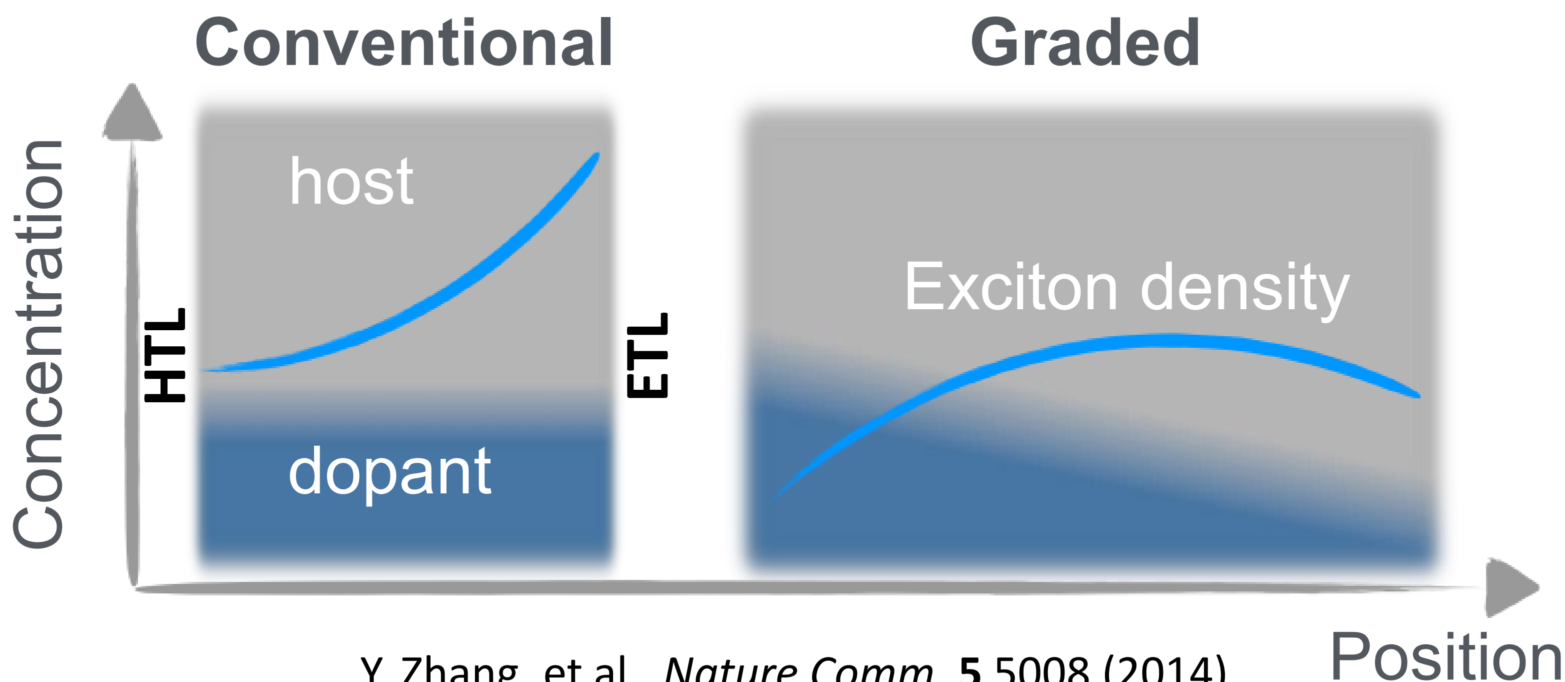



**Triplet energy (~2.9 eV) + polaron (~3.3 eV) = hot polaron (≥ 6 eV)**

N. Giebink, et al., *J. Appl. Phys.*, **103**, 044509 (2008).

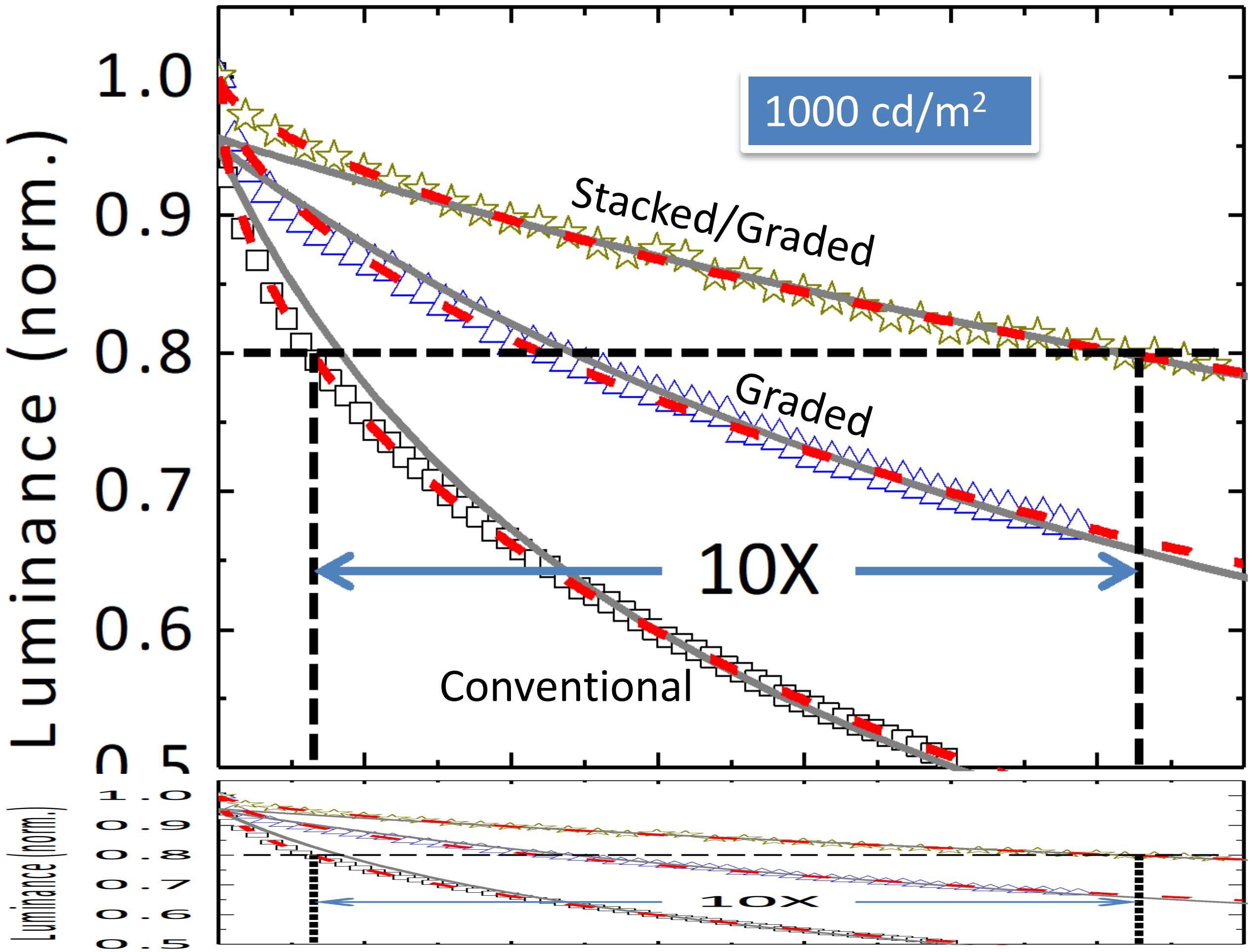
# Reducing Exciton Density to Increase Lifetime




Y. Zhang, et al., *Nature Comm.* **5** 5008 (2014)

# 10 X Blue PHOLED Lifetime Improvement

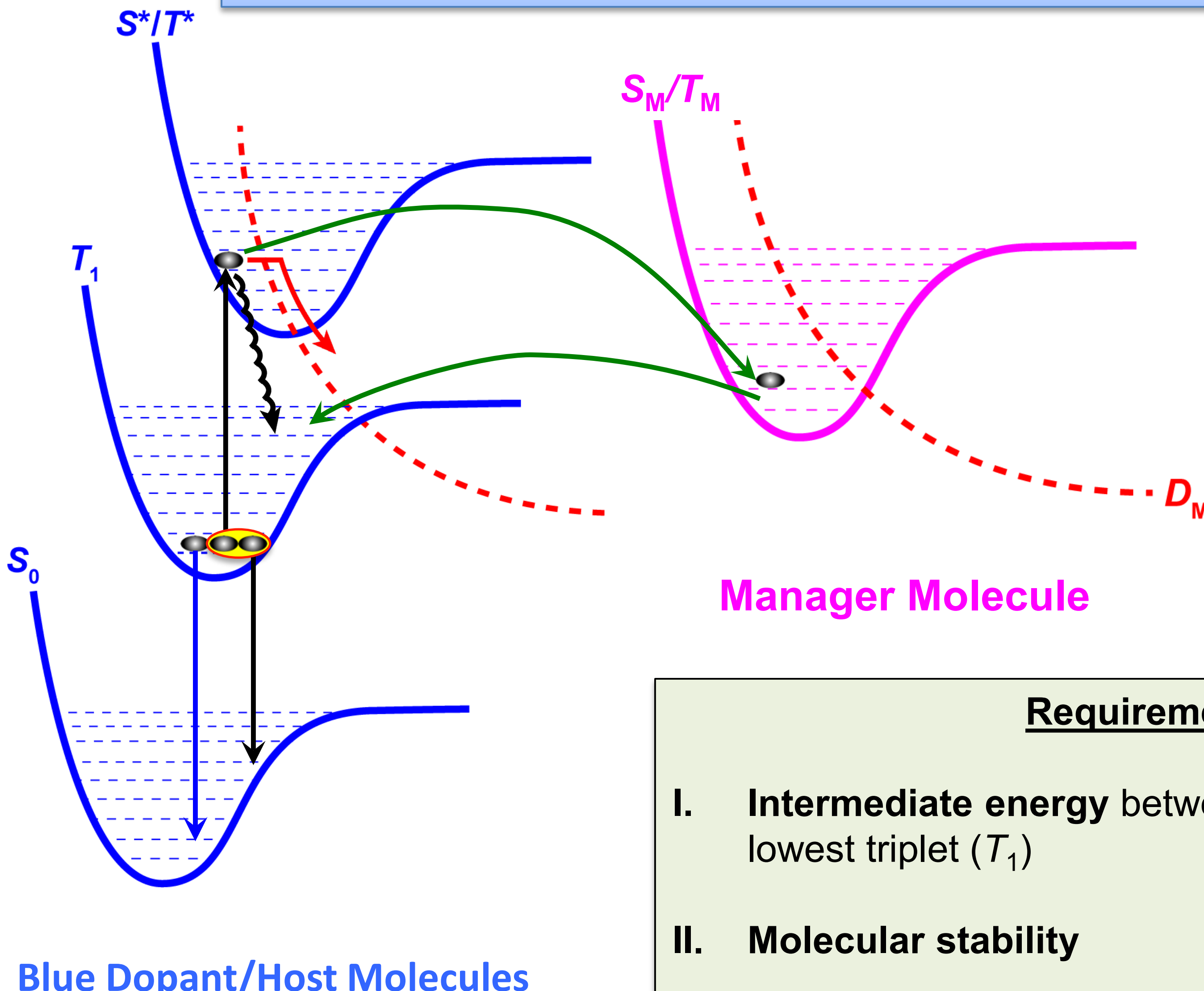



Y. Zhang, et al., *Nature Comm.* **5**, 5008 (2014)

**First significant increase** in blue PHOLED lifetime since their invention in 2000…
But still not good enough for lighting and displays.

# Hot excited state management

Solving the blue lifetime problem by **eliminating** excess energy




J. Lee, et al. Nat. Comm. (2017)

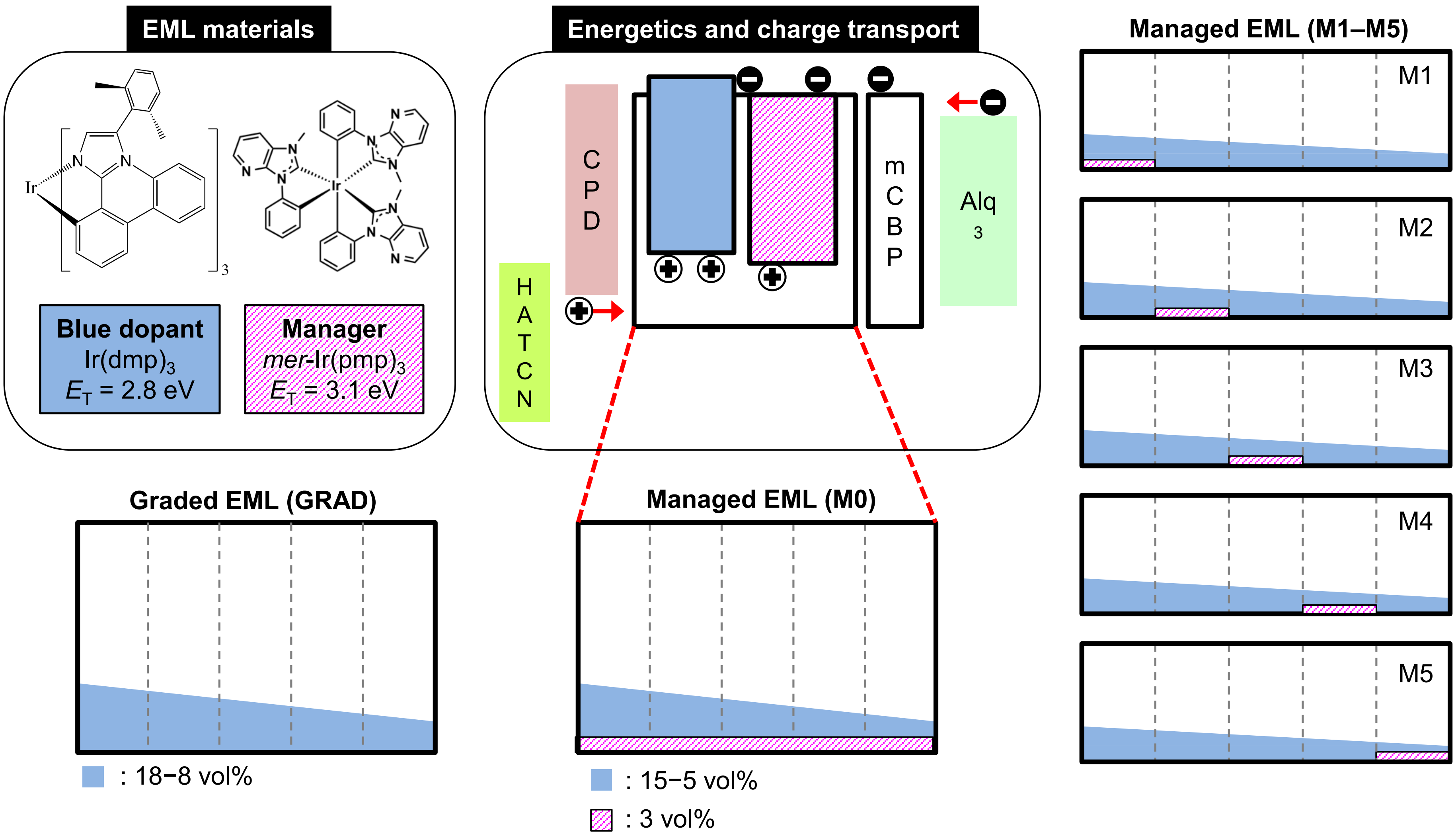
**Requirements**

I. **Intermediate energy** between hot state ($T^*$) and lowest triplet ($T_1$)

II. **Molecular stability**

III. **Fast energy transfer** from dopant/host to manager

# Managed blue PHOLEDs




J. Lee, et al. Nat. Comm. (2017)

# Performance Summary

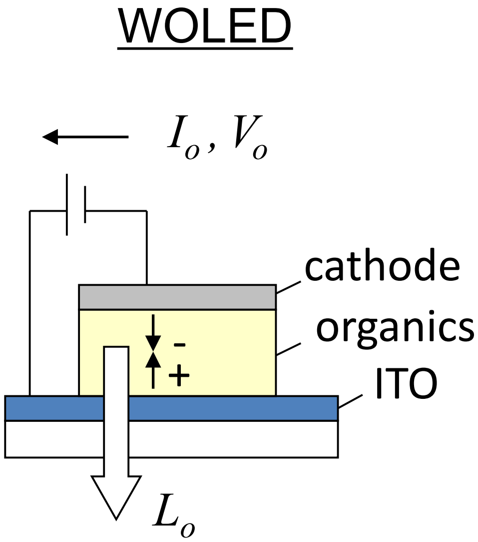
| Device | $J_0$ [mA/cm$^2$] | EQE [%] | $V_0$ [V] | CIE† | LT90 [hr] | T80 [hr] | ΔV(T90) [V] | ΔV(T80) [V] |
|---|---|---|---|---|---|---|---|---|
| **CONV** | 6.7±0.1 | 8.0±0.1 | 6.6±0.0 | [0.15, 0.28] | 27 ± 4 | 93 ± 9 | 0.3 ± 0.1 | 0.4 ± 0.1 |
| **GRAD** | 5.7±0.1 | 8.9±0.1 | 8.0±0.0 | [0.16, 0.30] | 47 ± 1 | 173 ± 3 | 0.6 ± 0.1 | 0.9 ± 0.1 |
| **M0** | 5.5±0.1 | 9.4±0.1 | 9.2±0.0 | [0.16, 0.30] | 71 ± 1 | 226 ± 9 | 0.9 ± 0.1 | 1.2 ± 0.1 |
| **M1** | 5.4±0.1 | 9.5±0.1 | 8.8±0.1 | [0.16, 0.29] | 99 ± 3 | 260 ± 15 | 1.2 ± 0.1 | 1.6 ± 0.1 |
| **M2** | 5.4±0.1 | 9.3±0.0 | 8.9±0.1 | [0.16, 0.31] | 103 ± 0 | 285 ± 8 | 0.7 ± 0.1 | 1.0 ± 0.1 |
| **M3** | 5.3±0.1 | 9.6±0.0 | 9.0±0.1 | [0.16, 0.30] | 141 ± 11 (5.2X) (3.0X) | 334 ± 5 (3.5X) (1.9X) | 1.1 ± 0.1 | 1.5 ± 0.2 |
| **M4** | 5.2±0.1 | 9.6±0.2 | 8.6±0.0 | [0.16, 0.31] | 126 ± 7 | 294 ± 16 | 1.0 ± 0.1 | 1.3 ± 0.1 |
| **M5** | 5.1±0.1 | 9.9±0.1 | 8.6±0.0 | [0.16, 0.31] | 119 ± 6 | 306 ± 3 | 0.9 ± 0.1 | 1.2 ± 0.1 |

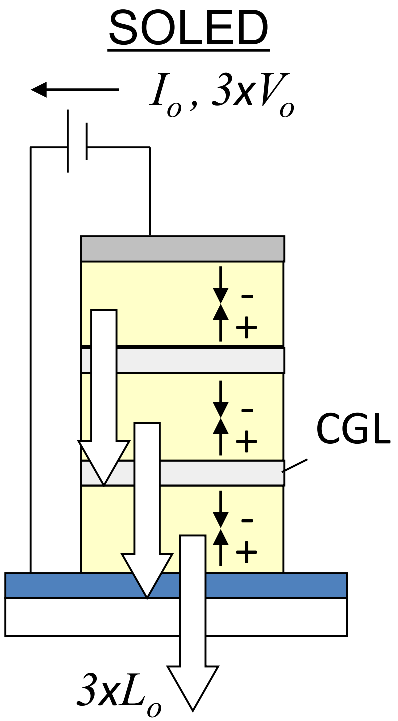
J. Lee, et al. Nat. Comm. (2017)

# WOLED vs. SOLED Lifetime Comparison

| **Panel 15 cm x 15 cm 82% fill factor** | **Single Unit WOLED*** | **2 Unit WSOLED** |
|---|---|---|
| **Luminance [cd/m²]** | **3,000** | **3,000** |
| **Efficacy [lm/W]** | **49** | **48** |
| **CRI** | **83** | **86** |
| Luminous Emittance [lm/m²] | 7,740 | 7,740 |
| Voltage [V] | 4.3 | 7.4 |
| 1931 CIE | (0.471, 0.413) | (0.454, 0.426) |
| Duv | 0.000 | 0.006 |
| CCT [K] | 2,580 | 2,908 |
| **Temperature [°C]** | **27.2** | **26.2** |
| **$LT_{70}$ [hrs]** | **4,000** | **13,000** |

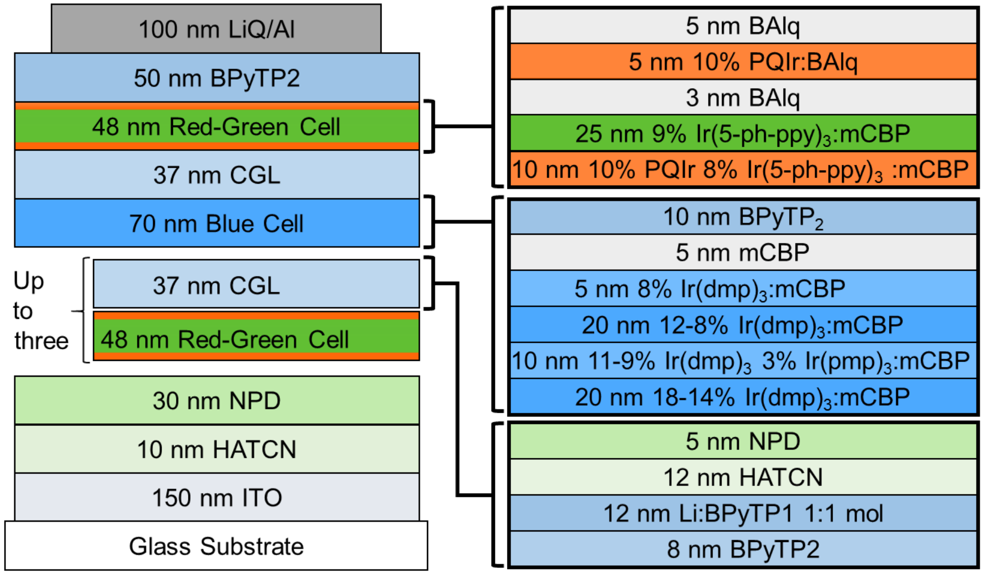
SOLED : ~ 3x $LT_{70}$ improvement vs. single unit WOLED with similar color and power efficacy




P. Levermore et al, **SID Digest,** 2011

# Putting Management to Work: Long lived all phosphor stacked WOLEDs

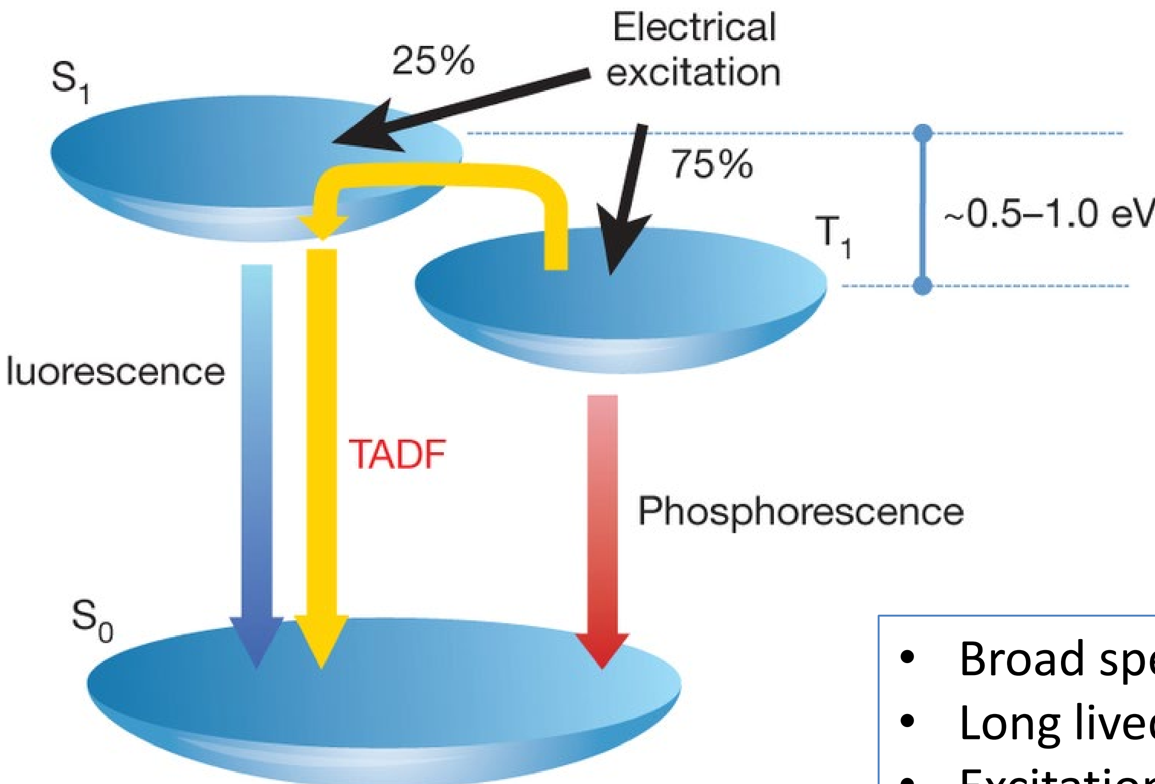



- Max Luminance > 200,000 nits
- 50 lm/W max
- CCT = 2780K
- CRI=89

| | With outcoupling | | |
|---|---|---|---|
| | T70 1000 nit ($x10^3$ hr) | T70 3000 nit ($x10^3$ hr) | $\Delta V/V_0$ (T70) (%) |
| SWOLED | 80±40 | 14±5 | ~+10% |

| T70 | SWOLED |
|---|---|
| ΔCCT | -360 K |
| ΔCRI | -0.8 |
| ΔCIE | (0.03,0) |

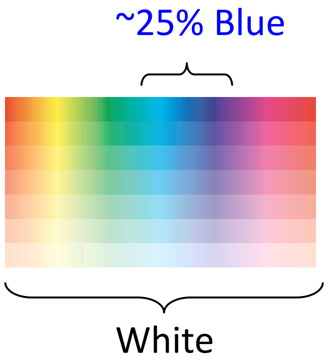
# What about TADF?

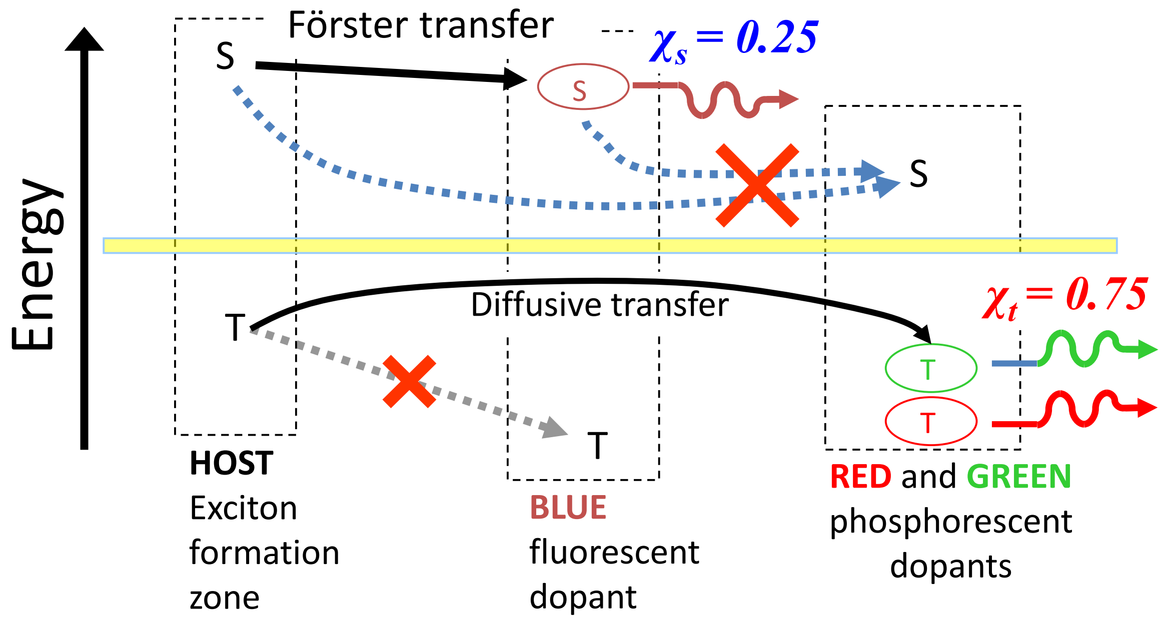



- Broad spectra
- Long lived triplets: 2-20μs
- Excitations maintained in triplet manifold
- Identical degradation mechanism to long-lived blue PHOLEDs
  - Can benefit from same solutions

Uoyama, et al., Nature 492, 234–238 2012

# Finding the Middle Ground: Fluorescent/Phosphorescent WOLEDs




- Singlet and triplet excitons harvested along independent channels → Resonant transfer of both excitonic species is independently optimized:
  - High energy singlet excitons for **blue** emission
  - Remainder of lower-energy triplet excitons for **green** and **red** emission

**Minimizing exchange energy losses**

**Potential for 100% IQE**

**More stable color balance**

**Enhanced stability**

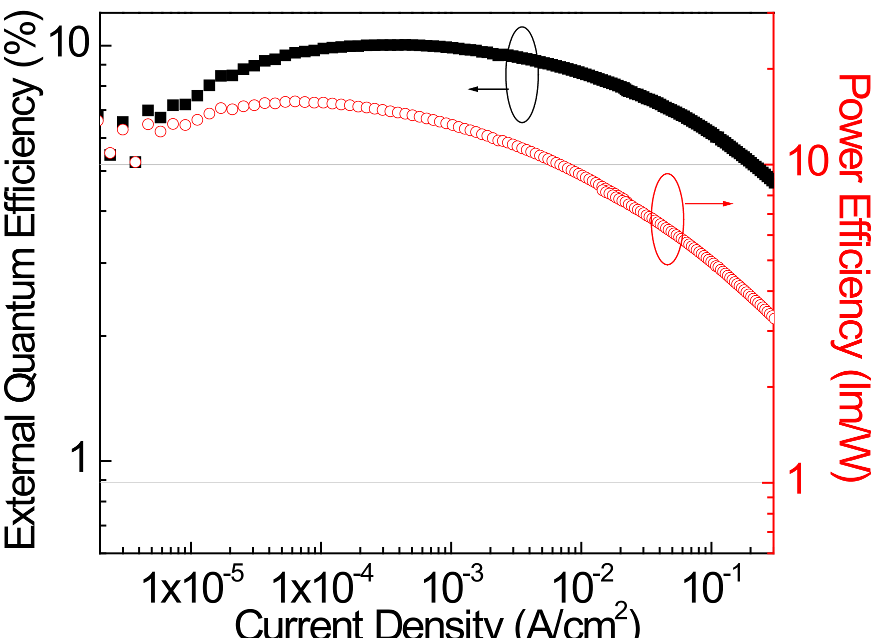
(Y. Sun, et al., *Nature*, **440**, 908, 2006)

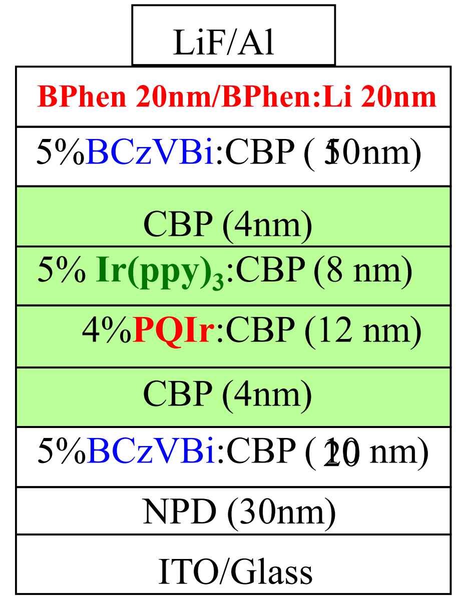
# Performance of WOLED

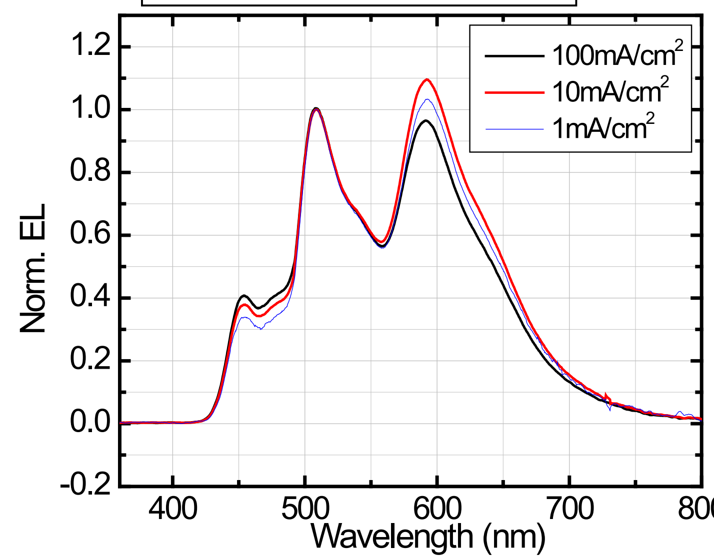
(Y. Sun, et al., *Nature*, **440**, 908, 2006)

*Forward viewing:*

- Quantum Efficiency (10.0±0.2)%
- Power Efficiency (15.8±0.3) lm/W
- Color Rendering Index (CRI): **84** at 1, 10 mA/cm$^2$, 83 at 100 mA/cm$^2$
- CIE: (0.40, 0.44) → (0.39, 0.43)



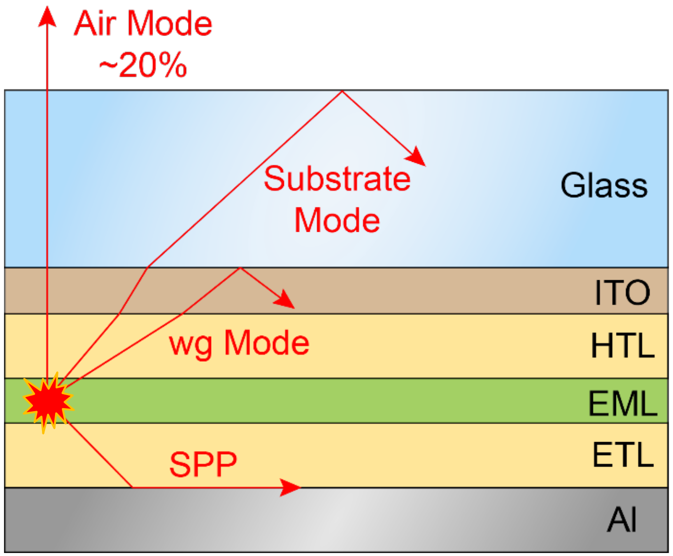



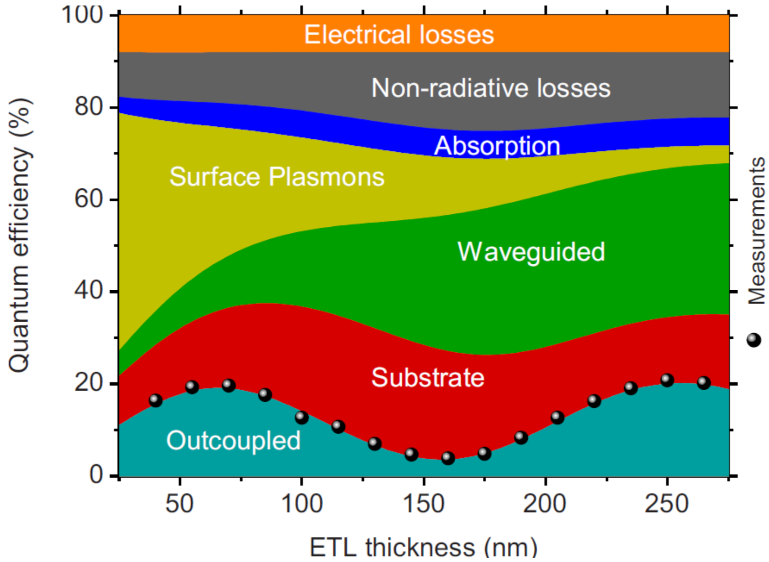




**(see poster by Mark Thompson)**

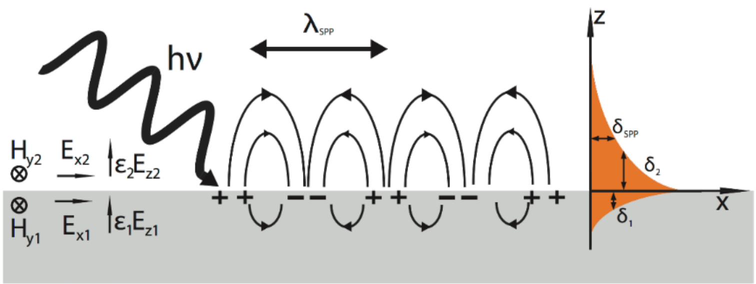
# Getting all the light out

- $\eta_{EQE} = \eta_{IQE}\,(\sim100\%) \times \eta_{Ext} \approx 20\%$



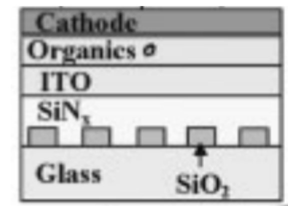

- OLED Loss Channels
  - Substrate mode
  - Waveguide mode
  - **Surface plasmon polariton (SPP)**
  - **Metal absorption**

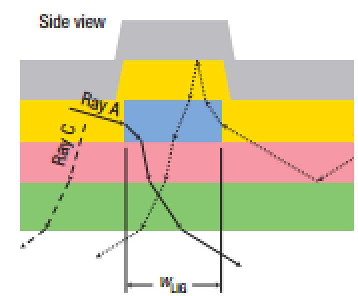


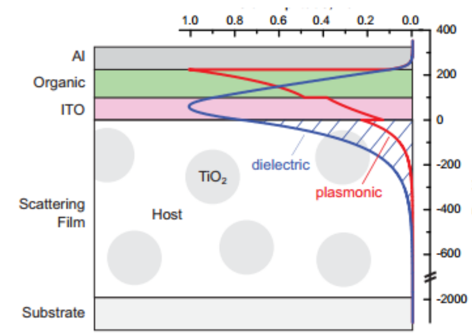

SPP Modes

# Getting all the light out, or "no photon left behind"

- **Good solutions**
  - Inexpensive
  - Viewing angle & wavelength independent
  - Independent of OLED structure
- **Examples**
  - Optical gratings or photonic crystals[1]
  - Corrugations or grids embedded in OLED[2]
  - Nano-scale scattering centers[3]
  - Molecular dipole orientation management



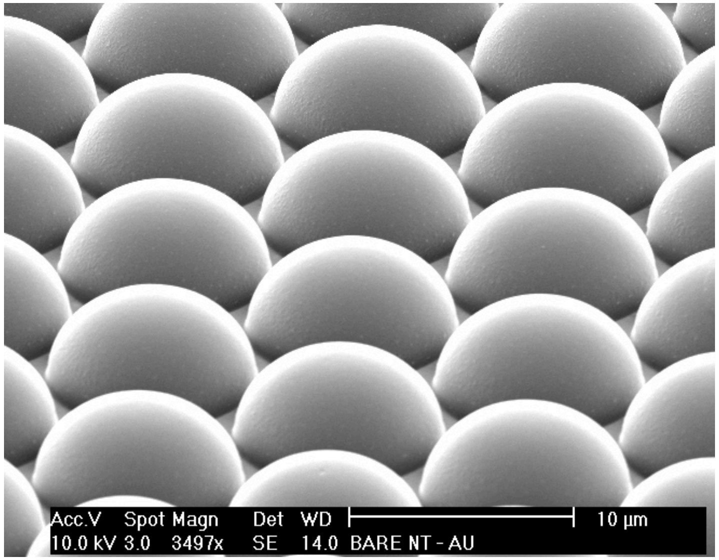




[1]Y .R. Do, et al, *Adv. Mater*. **15**, 1214 (2003).
[2]Y. Sun and S.R. Forrest, *Nat Phot*. **2**, 483 (2008).
[3]Chang, H.-W. *et al*. *J. Appl. Phys.* **113,** - (2013).

# Substrate Modes: ~2X Improvement

$\eta_{ext}$~40%



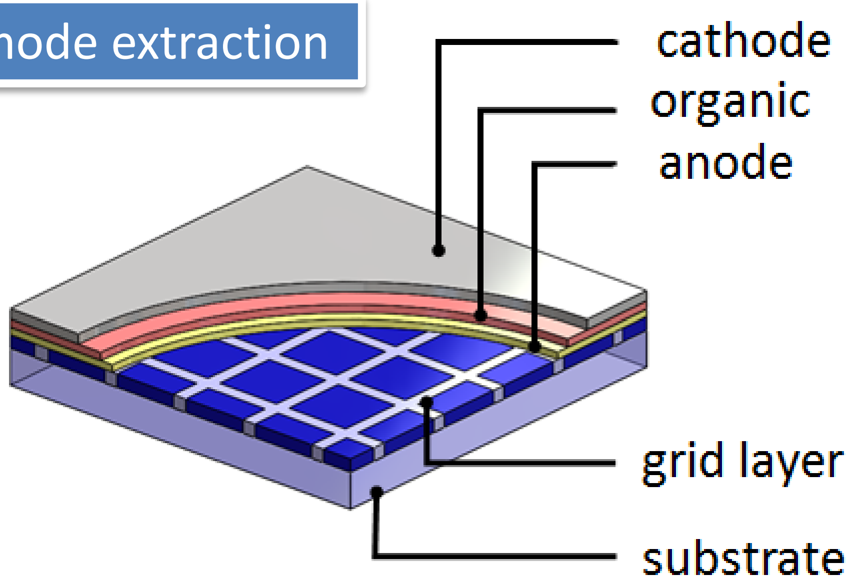

Microlens arrays
- Polymer hemispheres
- Much smaller than pixel

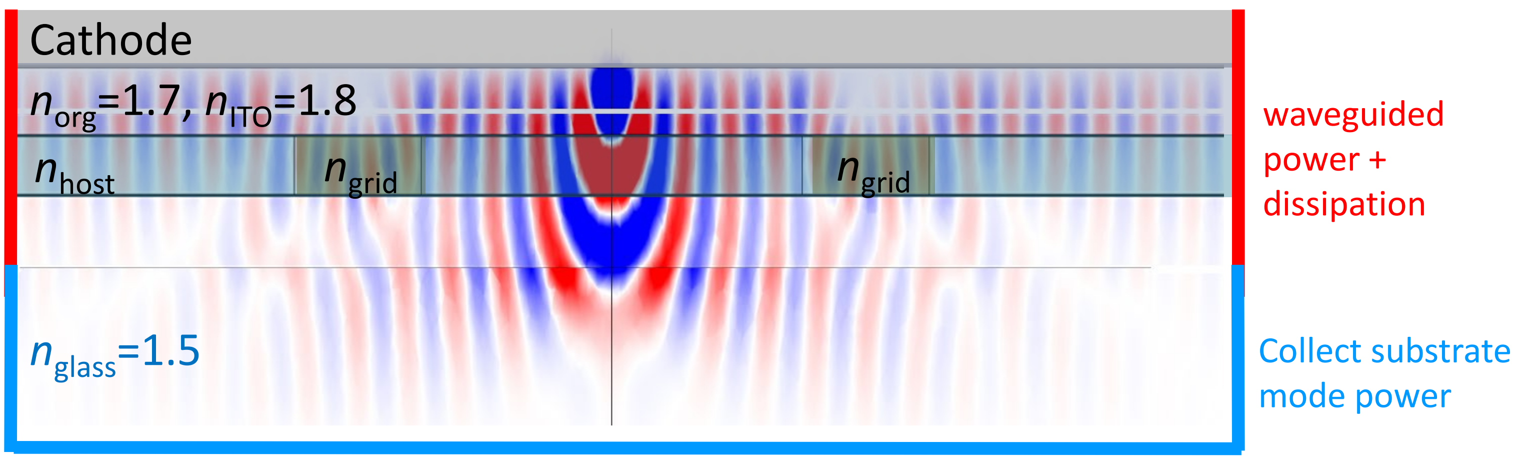
Möller, S. & Forrest, S. R. 2001. *J. Appl. Phys.,* 91**,** 3324.

# Extracting Waveguide Modes: Sub-Anode Grid

$\eta_{ext}$~60% with substrate mode extraction

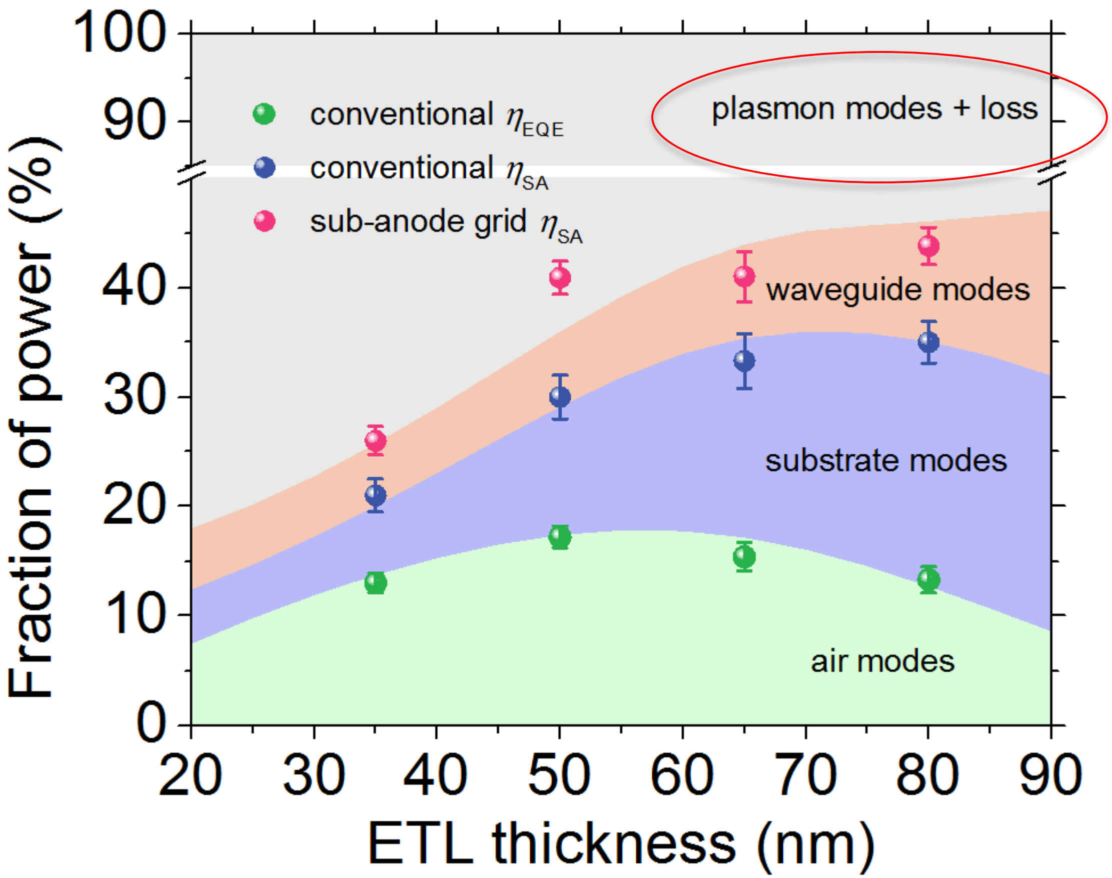
- A multi-wavelength scale dielectric grid between glass and transparent anode (sub-anode grid)
- <u>The grid is out of the OLED active region</u>
- Waveguided light is scattered into substrate and air modes



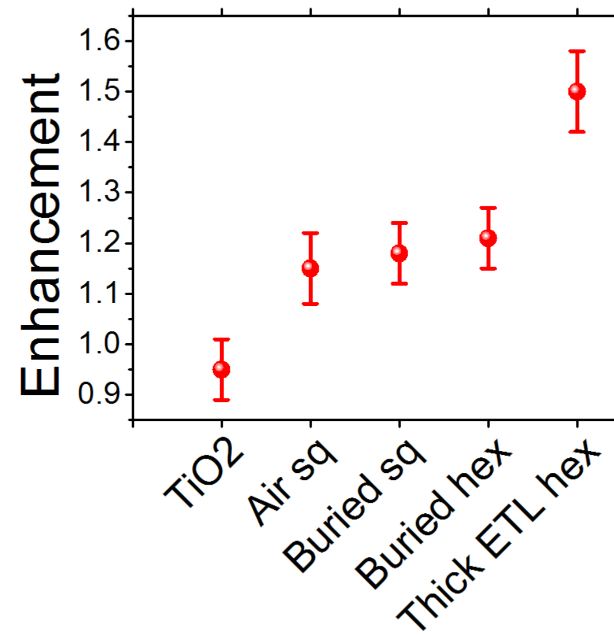




Qu ,Slootsky, Forrest, *Nature Photonics* (2015)

# Optical Power Distribution




2nm $MoO_3$/40nm CBP/15nm CBP:Ir(ppy)$_3$/xnm TPBi/1nm LiF/Al



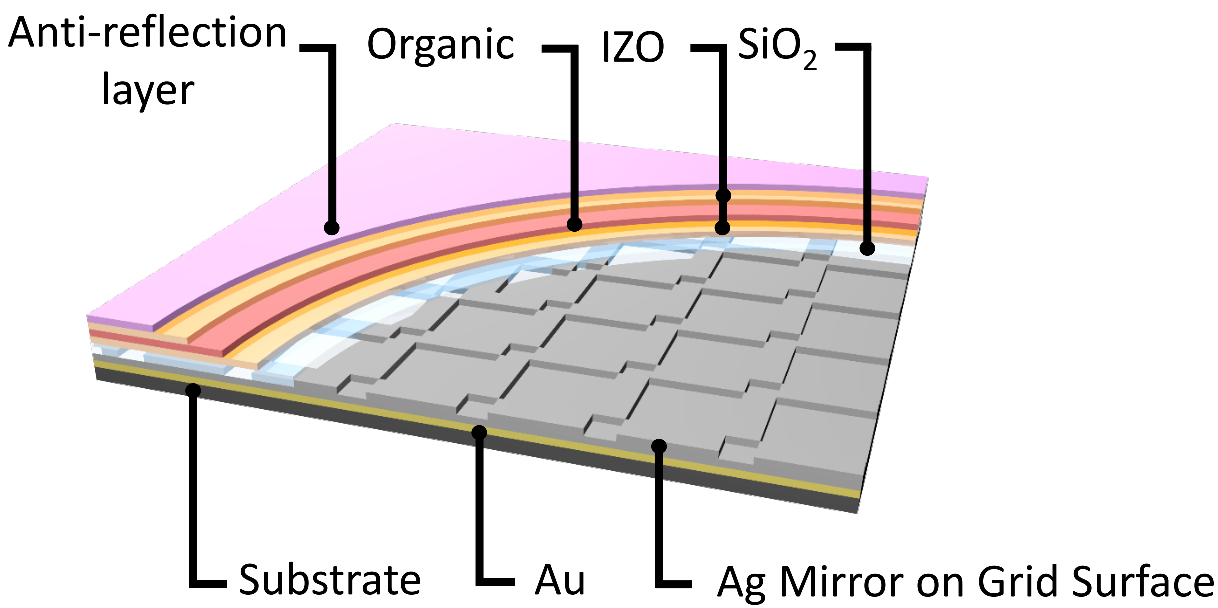

Thick-ETL organic structure:

340nm grid/70nm ITO/2nm $MoO_3$/40nm TcTa/15nm CBP: Ir(ppy)$_3$/10nm TPBi/230nm Bphen:Li/Al

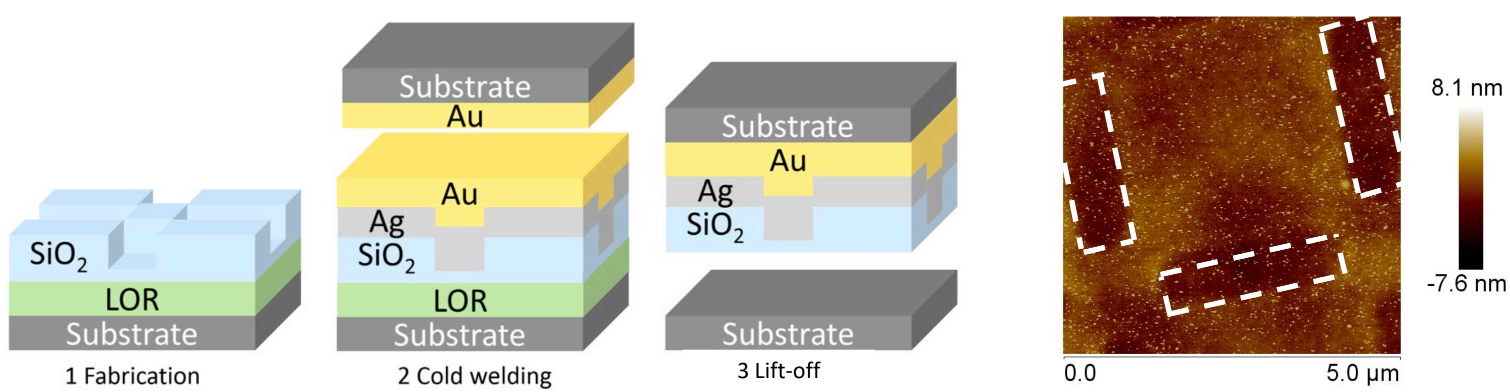
# Getting Rid of SPPs Using Sub-Anode Grid + Mirror

Qu, et al. ACS Photonics, 2017

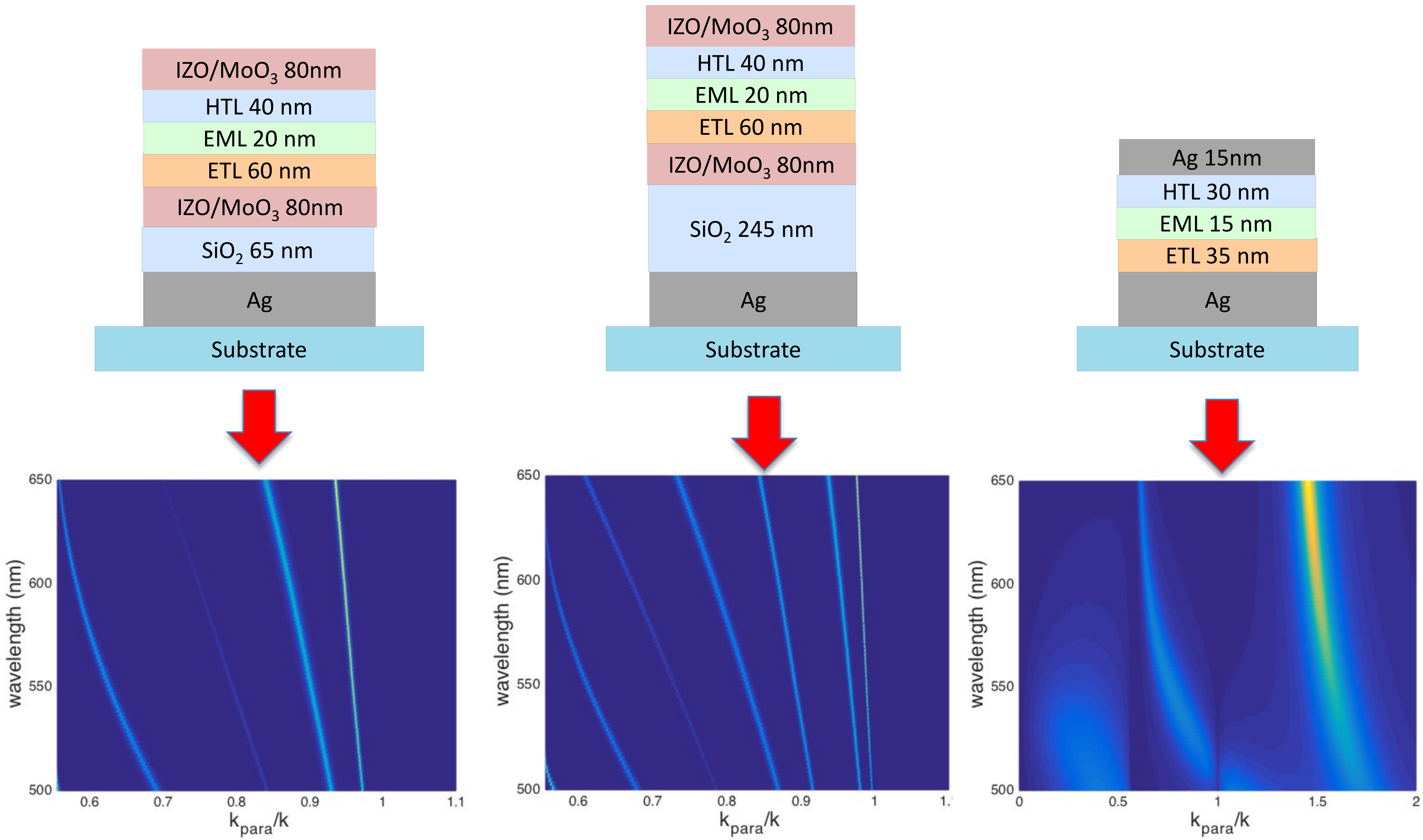
## Top Emitting OLED




## Substrate Fabrication

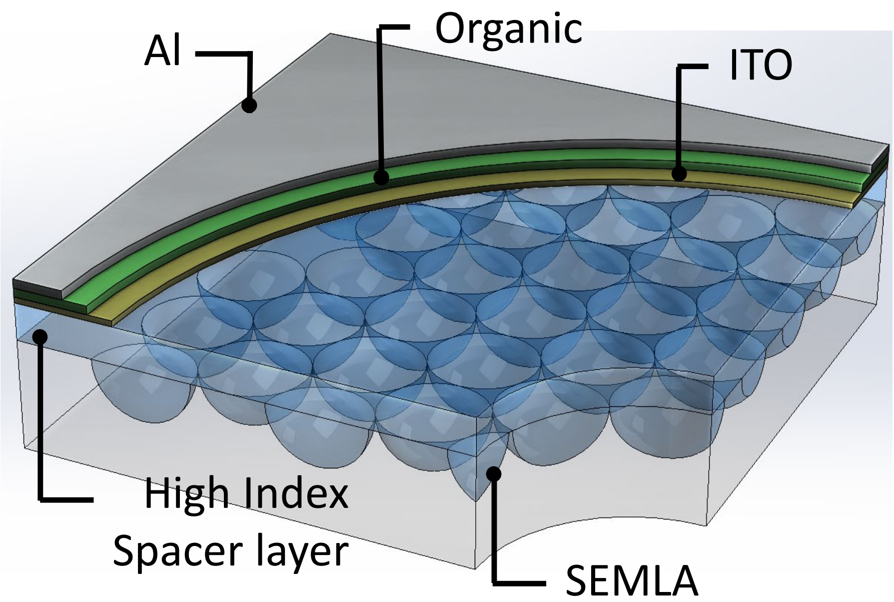


# Sub-electrode grid modeling

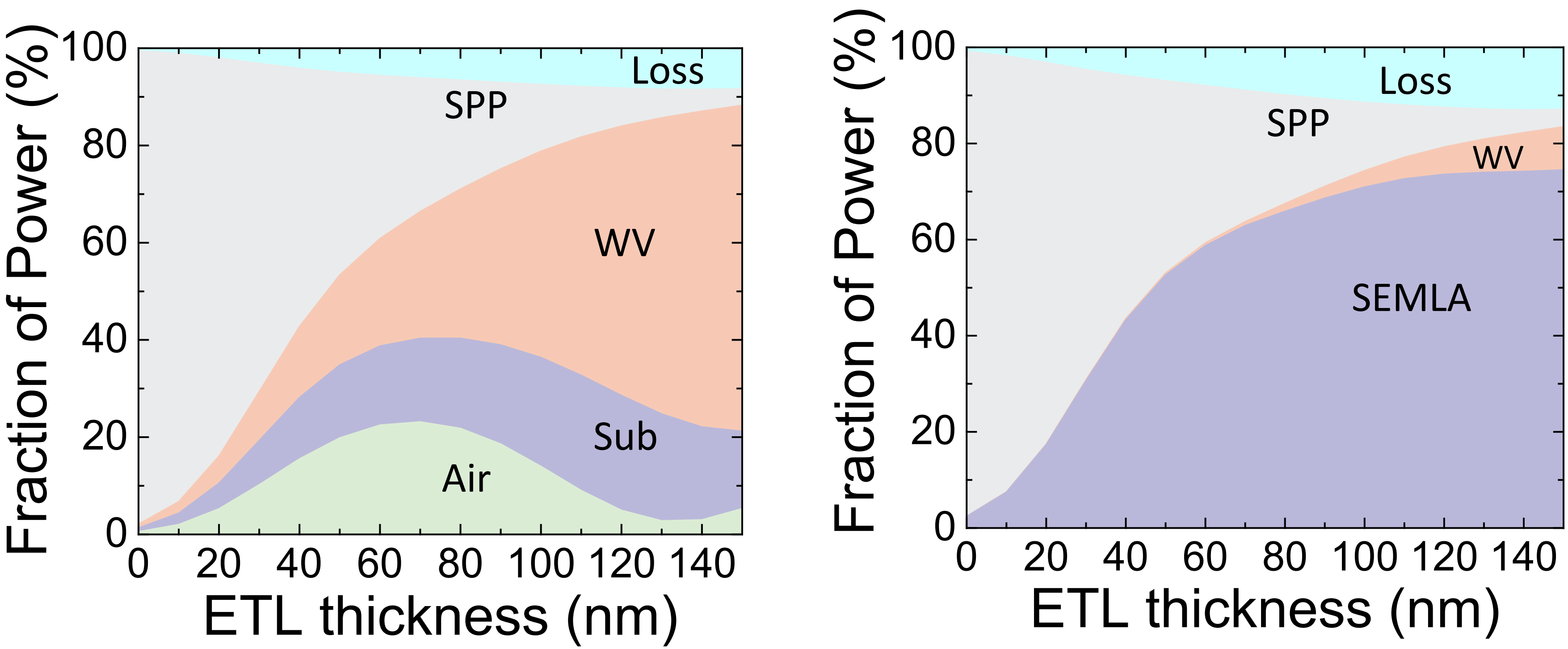



**Variable Waveguide Widths Prevent Mode Propagation**

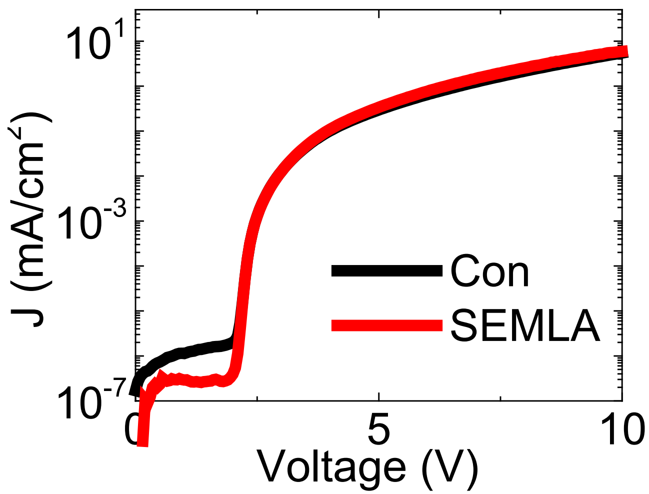
# Getting All the Light Out: Sub-Electrode Microlens Array (SEMLA)

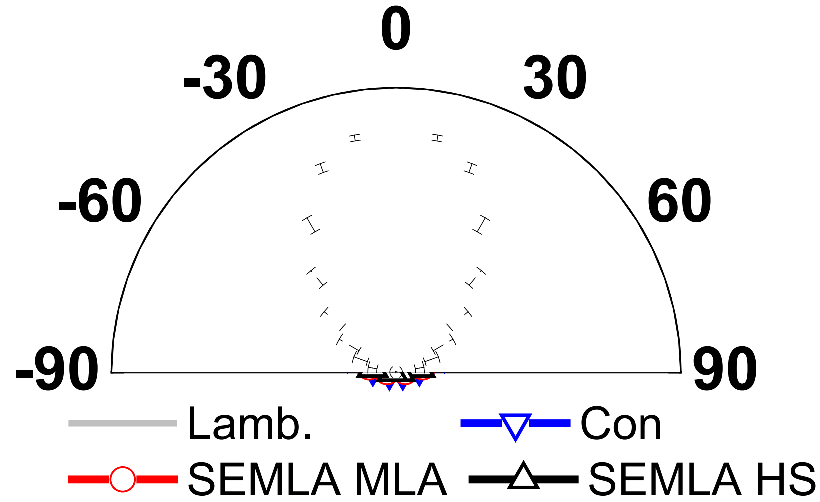


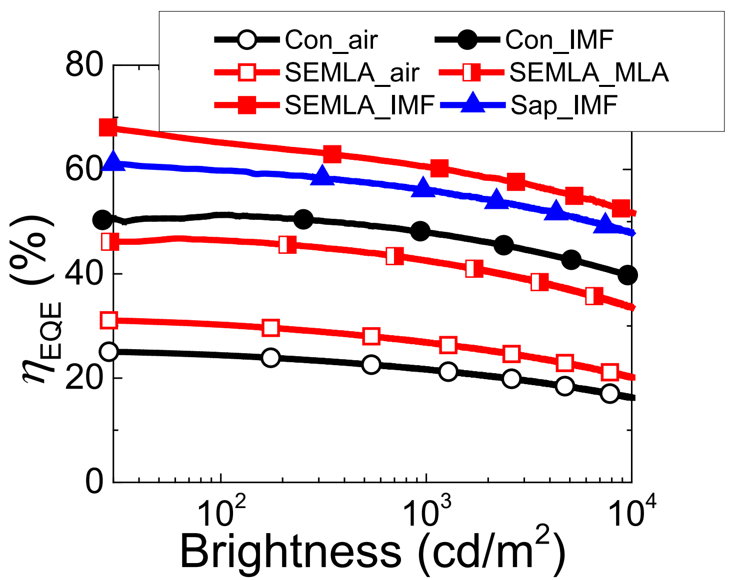

# SEMLAs Change the Outcoupling Landscape

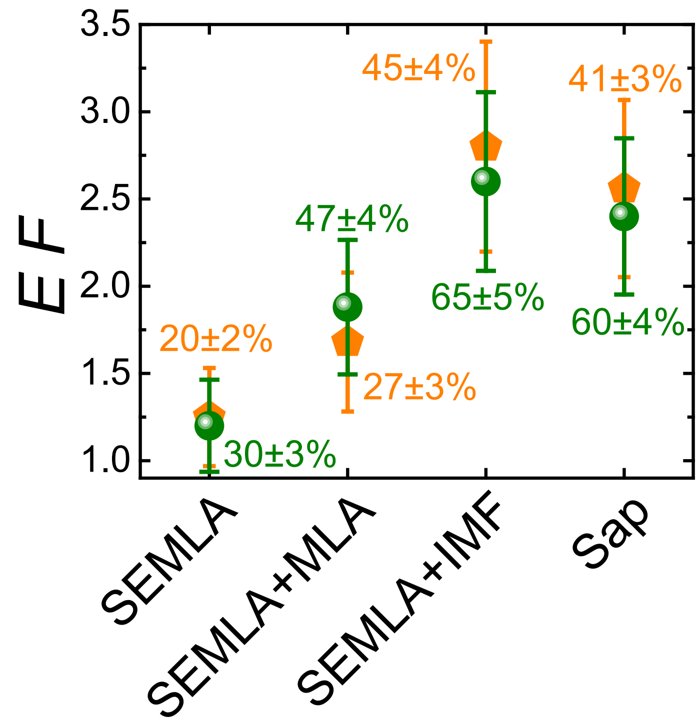


# SEMLA Performance

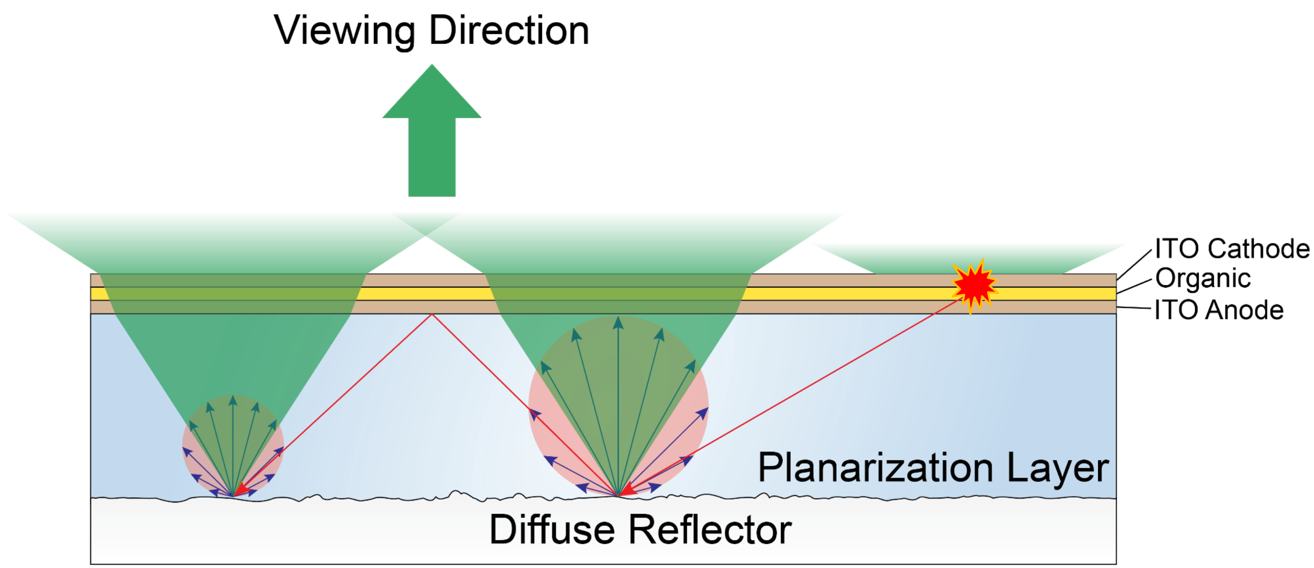


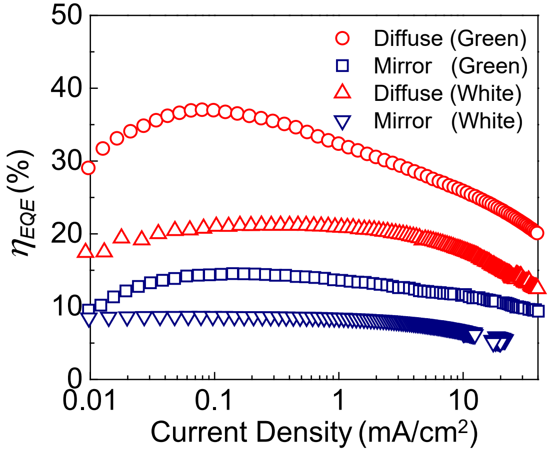



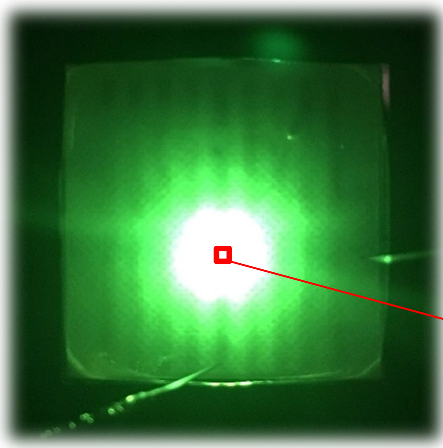



# Diffuse Reflectors: Low Cost & Simple




Teflon is the best diffuse dielectric reflector



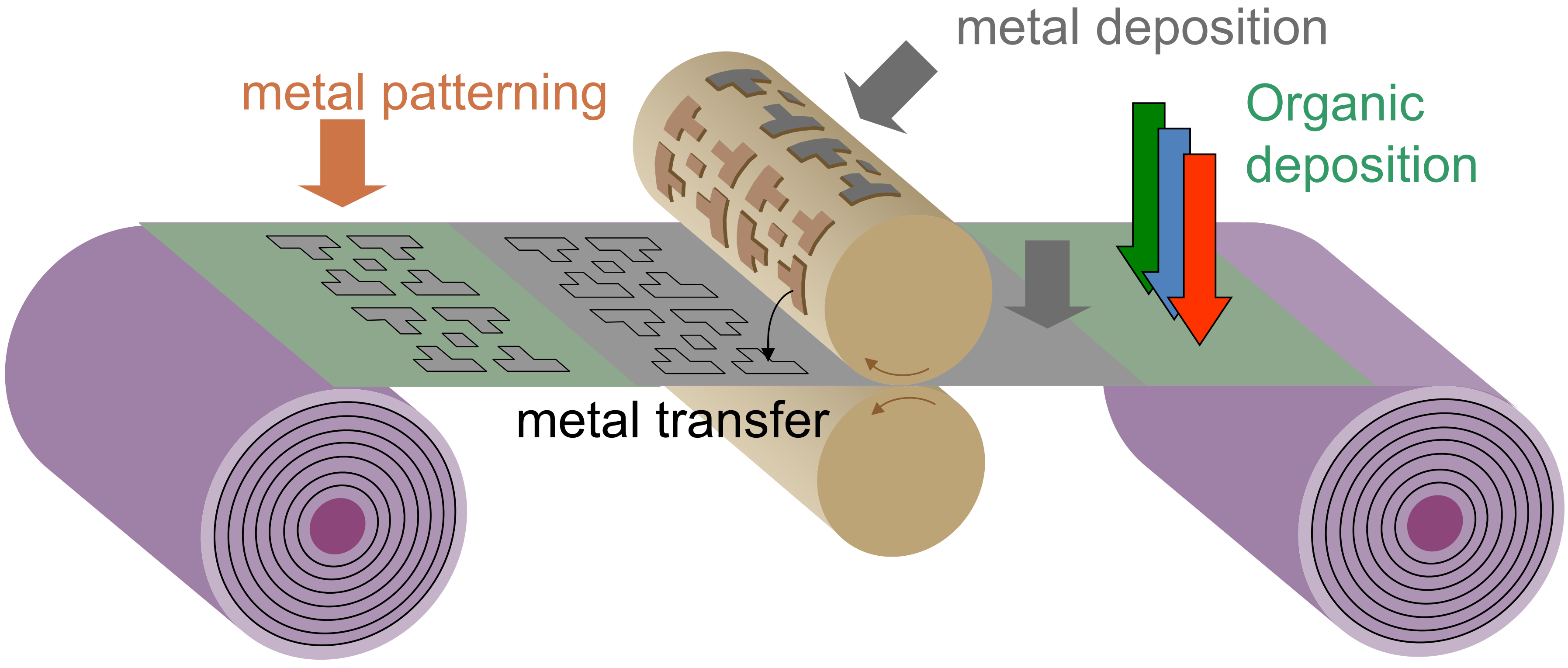



# Getting the Cost Out: Patterning & Deposition

- Purity is everything → Small molecule
- Multilayer structures important → Dry process
- Very inexpensive → High throughput
- Depends on how to make color & white
  - RGB stripes
  - Pixellated WOLEDs
  - RGB Pixels
- Options
  - Vacuum thermal evaporation
  - Organic vapor phase deposition….

# R2R-Processing of Organic Devices

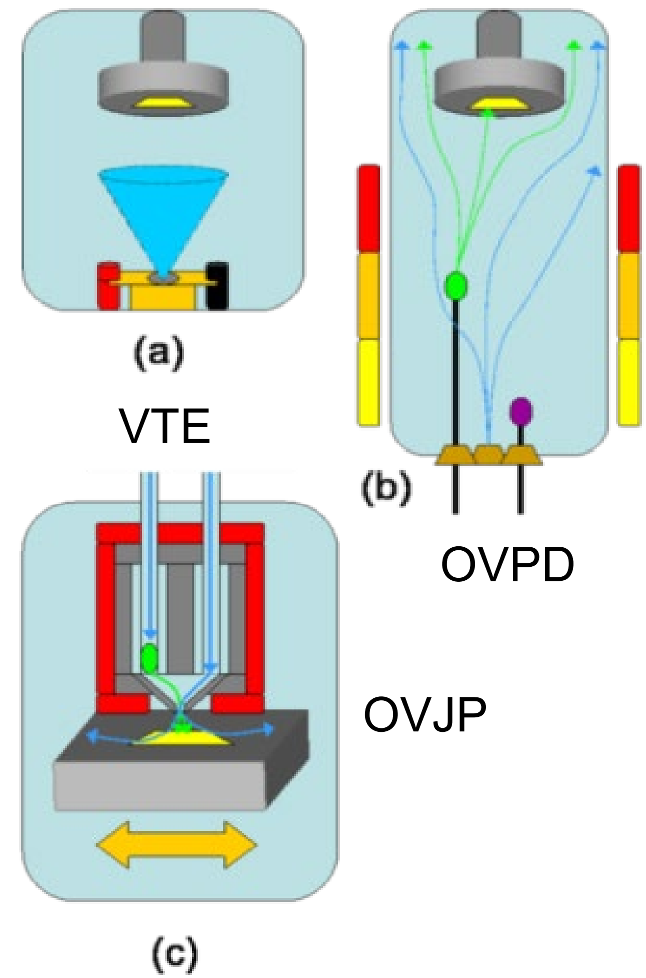
## Making Electronics "By the Mile"



# OLED Fabrication Processes

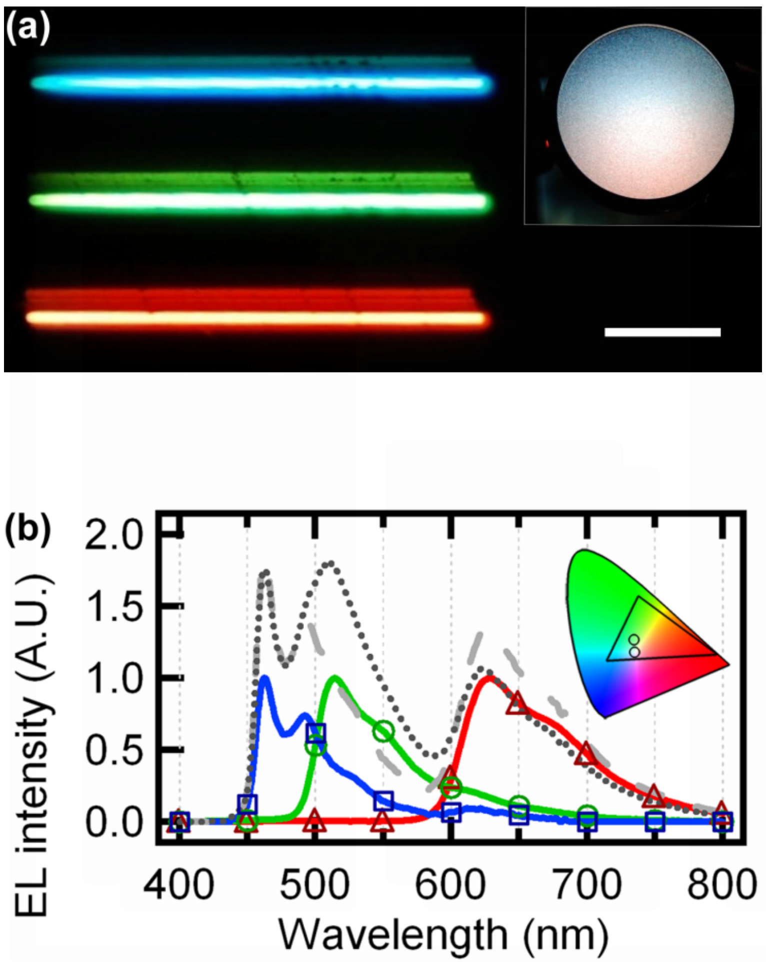
| | Vapor (PVD) | Condensed Phase |
|---|---|---|
| **Examples** | VTE<br>**OVPD**<br>**OVJP** | Inkjet<br>Nozzle Printing<br>LITI<br>µ-contact printing |
| **Materials** | Small molecules | Small molecules or polymers |
| **Multilayer Structures**<br>**Co-deposition** | Molecularly sharp interfaces<br>Even Mixing<br>Amorphous film | Less thickness ctrl.<br>May damage heterojunctions & complicate doping. |
| **Patterning** | Thin Metal Mask<br>**Direct Print** | Direct Print |
| **Atmosphere** | Vacuum | Inert Gas |
| **Media** | None | Solvent or xfer film |
| **Use** | Commercial & Research | Research |

## Organic PVD




Shtein *et al. J. Appl. Phys.* **93**, 7, 4005 (2003)

# Printed WOLEDs Using OVJP




| Process | OVJP | VTE |
|---|---|---|
| EQE (%) | 9.4 | 12.6 |
| PE (lm/W) | 4.7 | 4.9 |
| EQE (%) | 8.6 | 8.9 |
| PE (lm/W) | 16.5 | 13.3 |
| EQE (%) | 5.4 | 6.0 |
| PE (lm/W) | 4.2 | 5.5 |

M. Arnold, G. McGraw and R. Lunt, Appl. Phys. Lett., 2008

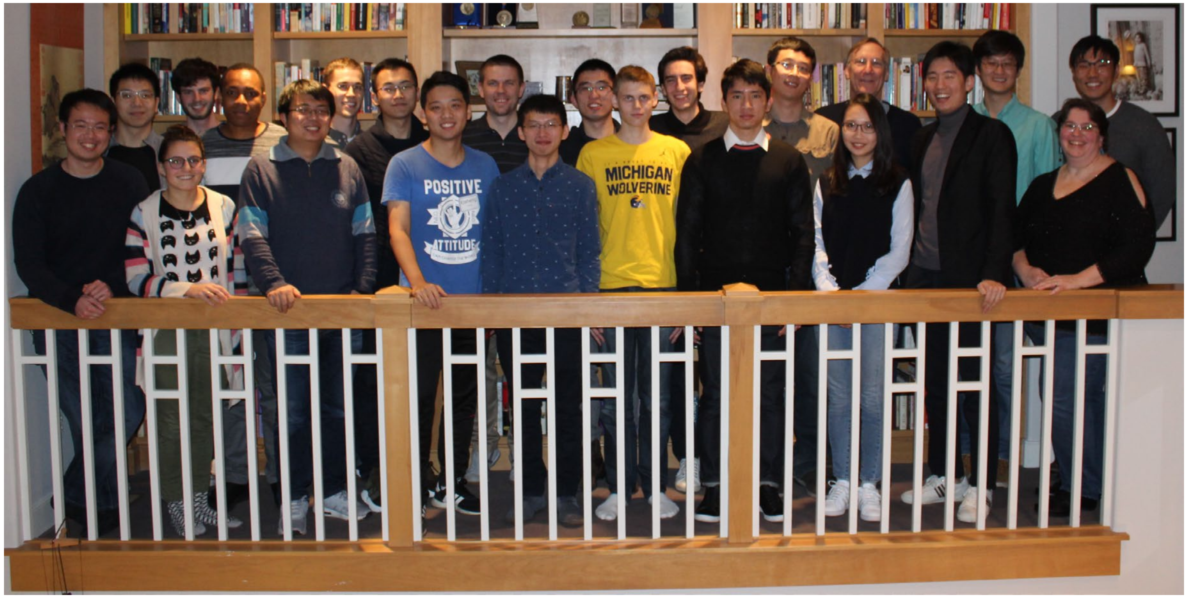
# Will OLEDs Play a Major Role in Lighting?

***ABSOLUTELY!***

- Large area, ultra-efficient color tunable, architecturally adaptable form factor make this an opportunity too good to miss
- But, there are still challenges
  - **Blue PHOLEDs** can possibly achieve >100X lifetime improvement over the graded solution using **excited state management**
  - Innovative means for getting the light out being developed
  - Patterning on large surfaces at low cost driven by display industry
  - And don’t forget the package!

# Acknowledgements


- Optoelectronic Components and Materials Group @ UM




- Mark Thompson and group @ USC

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