Week 10

Light emitters 3

Outcoupling Strategies

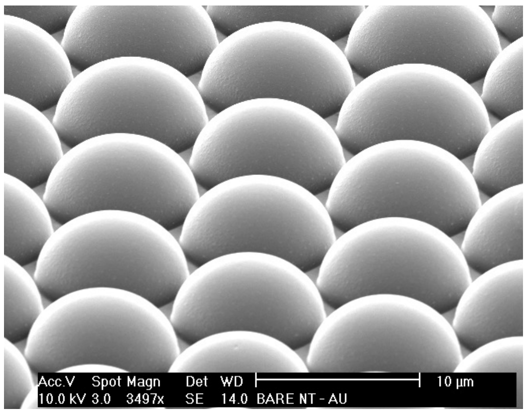
Reliability

Chapter 6.6.2-6.7

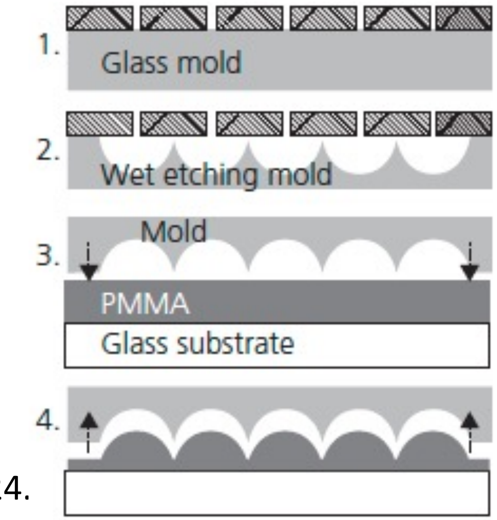
Substrate Mode Outcoupling: ~2X Improvement

η_{ext}~40%

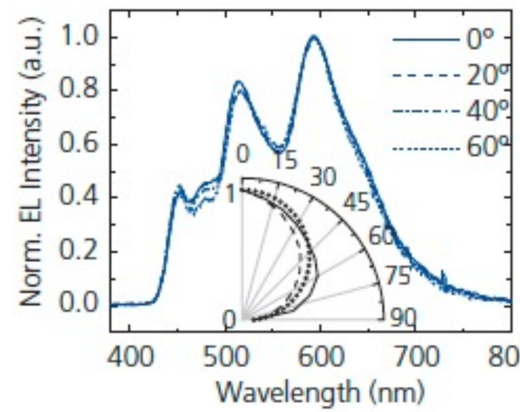
Microlens arrays: Polymer hemispheres much smaller than pixel



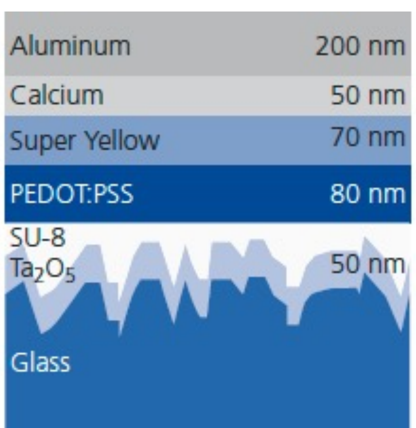
Möller, S. & Forrest, S. R. 2001. *J. Appl. Phys.,* 91**,** 3324.



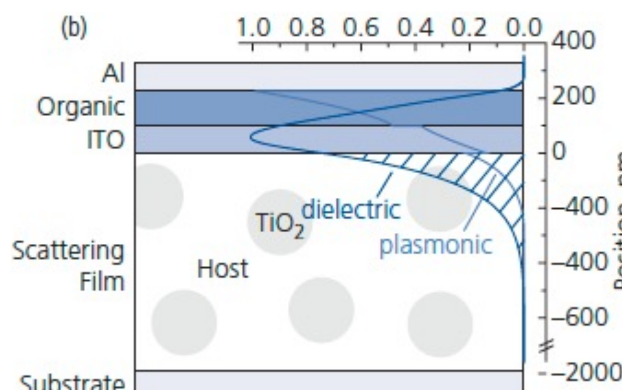
Fabrication sequence



Spectrum angle independent



Reidel, et al., Opt. Express 18 A631 (2010)



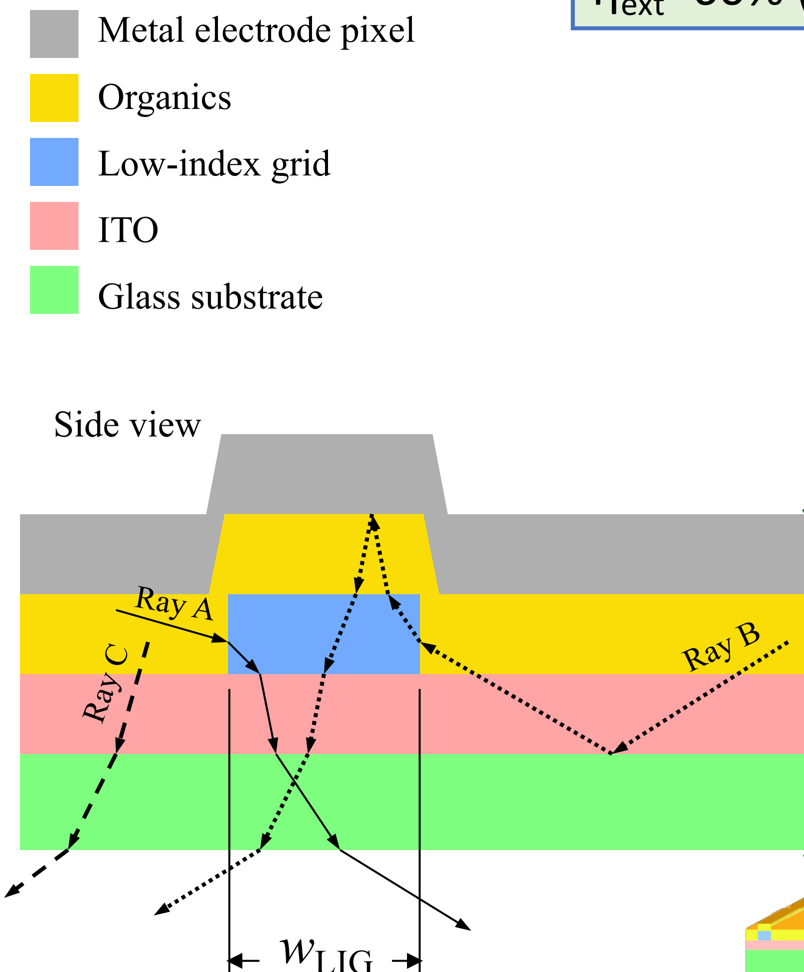
Chang, et al., J. Appl. Phys., 113 204502 (2013)

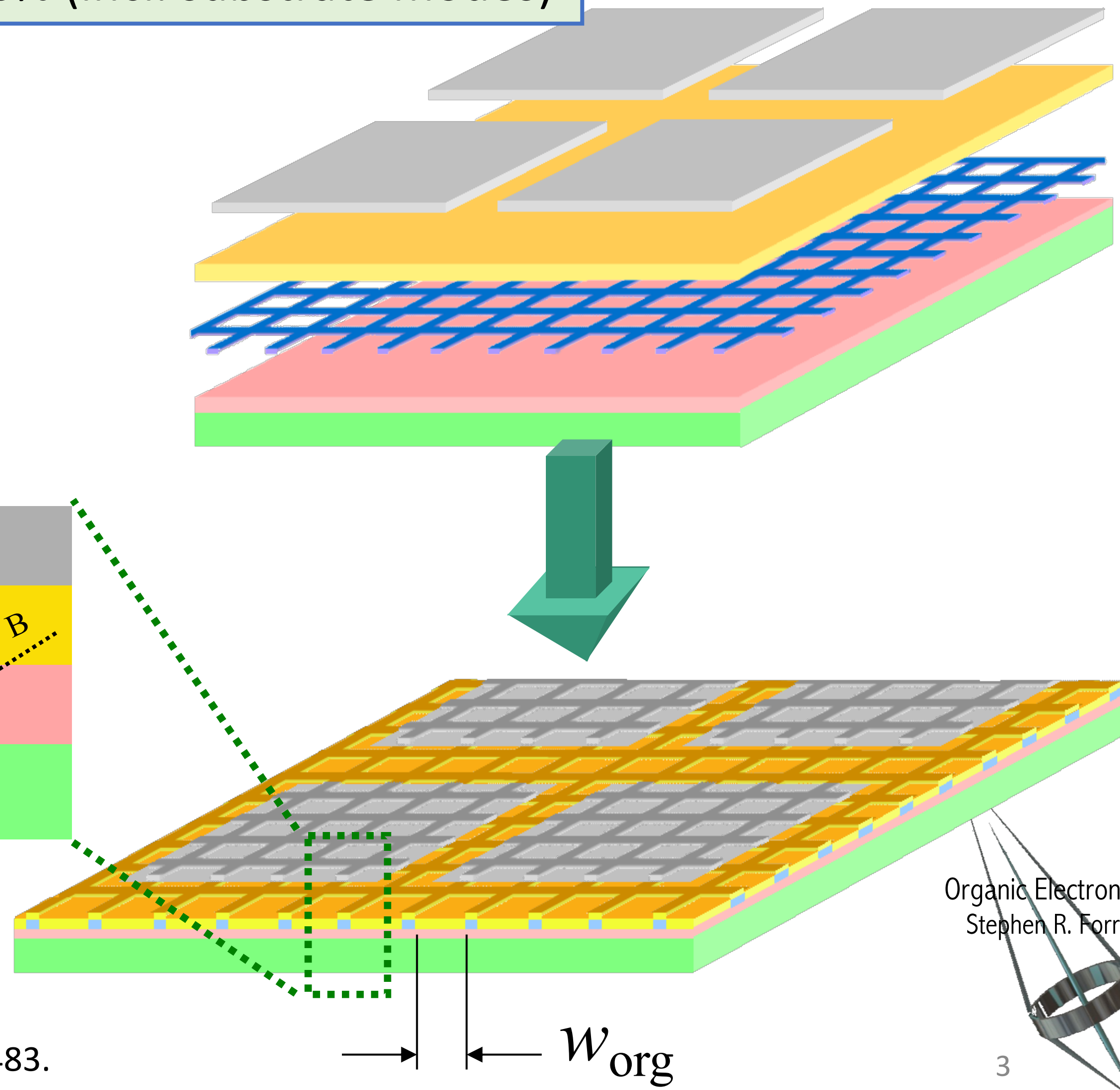
⇐ Scattering and surface roughness also can reduce substrate modes

Stephen R. Forrest

Waveguide Mode Outcoupling: Embedded Low Index Grid

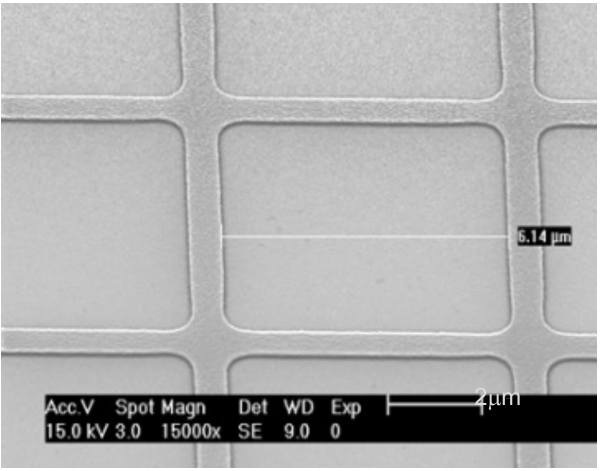
η_{ext}~60% (incl. substrate modes)

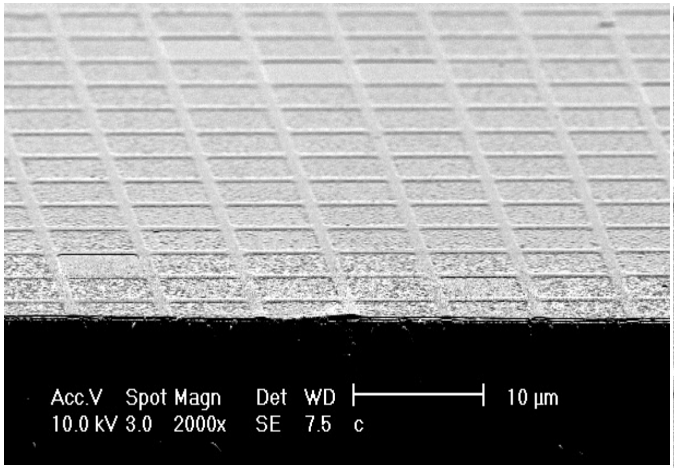


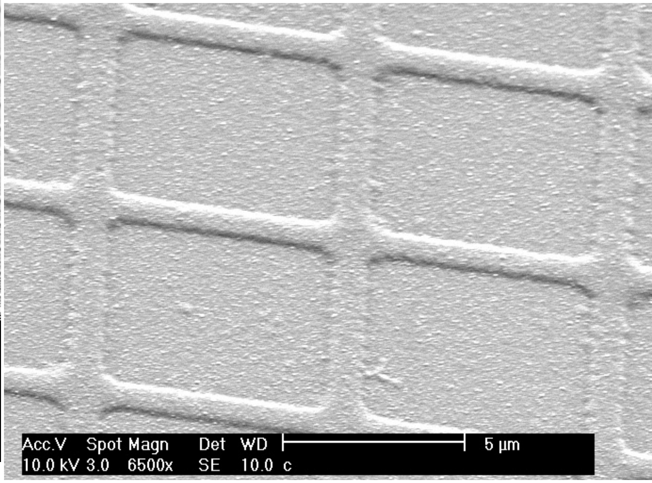


Sun, Y. & Forrest, S. R. 2008. *Nature Photon.*, **2**, 483.

Low Index Grid Images

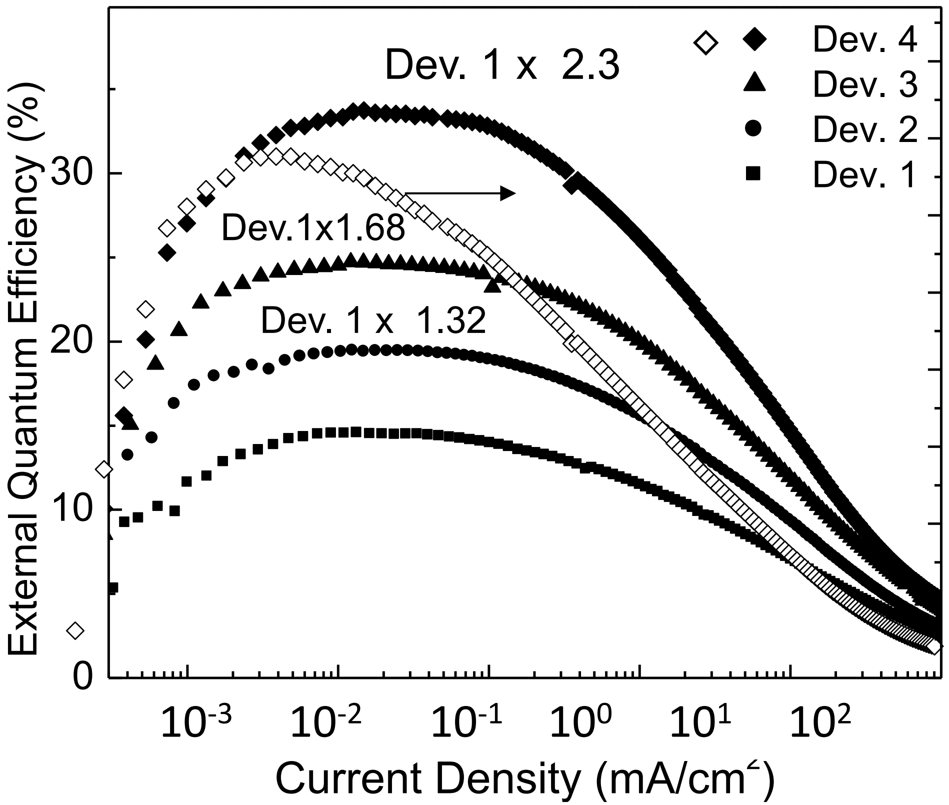


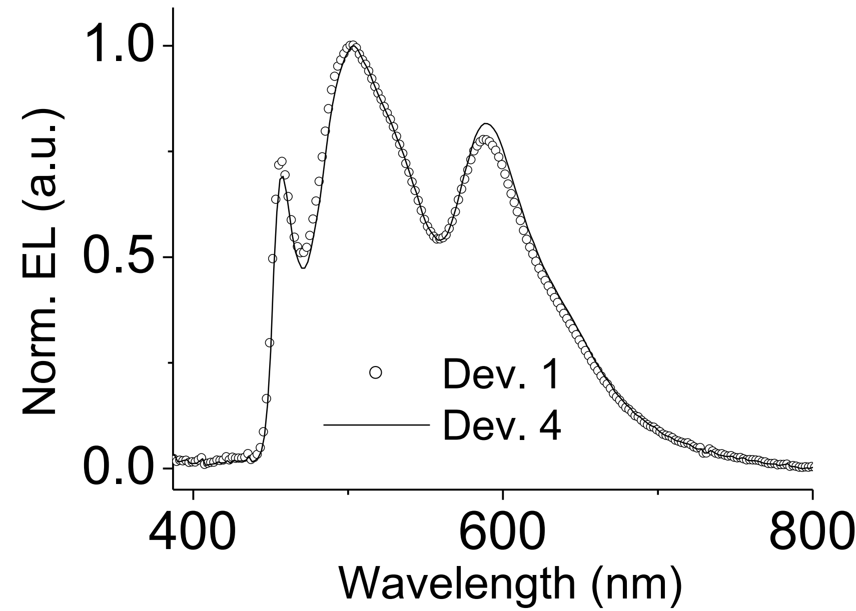




- OLED >> Grid size >> Wavelength
- Embedded into OLED structure
- May partially decouple waveguide mode from SPPs

Hybrid WOLED Performance Using Embedded Grids + Microlens Arrays





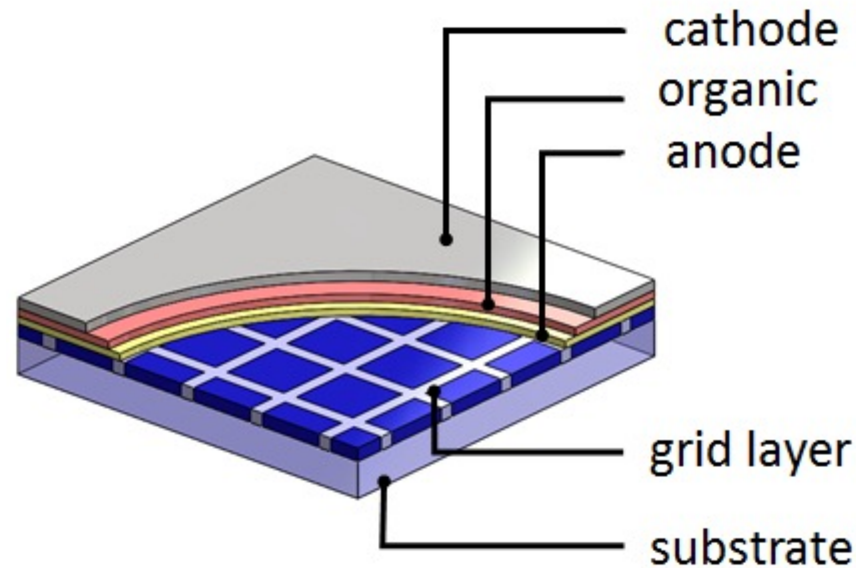
Method is Wavelength Independent

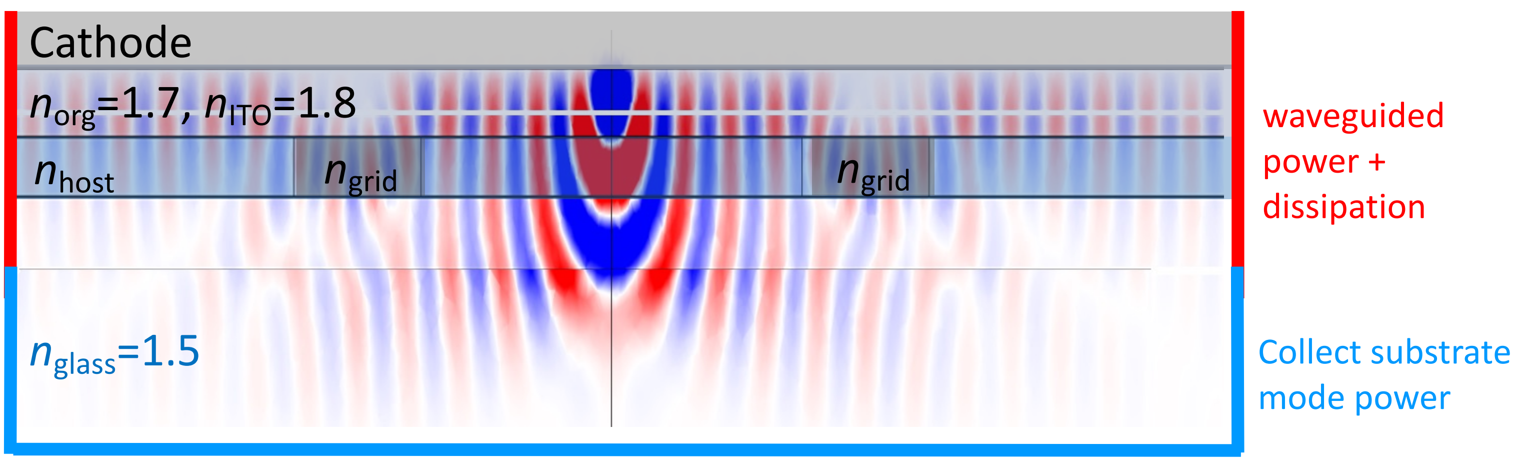
Device 1: Conventional
Device 2: LIG only
Device 3: Microlenses only
Device 4: LIG + Microlenses

Sun, Y. & Forrest, S. R. 2008. *Nature Photon.,* 2**,** 483.

A better approach: Sub-Anode Grid

- ❑ A multi-wavelength scale dielectric grid between glass and transparent anode (sub-anode grid)
- ❑ The grid is removed from the OLED active region
- ❑ Waveguided light is scattered into substrate and air modes





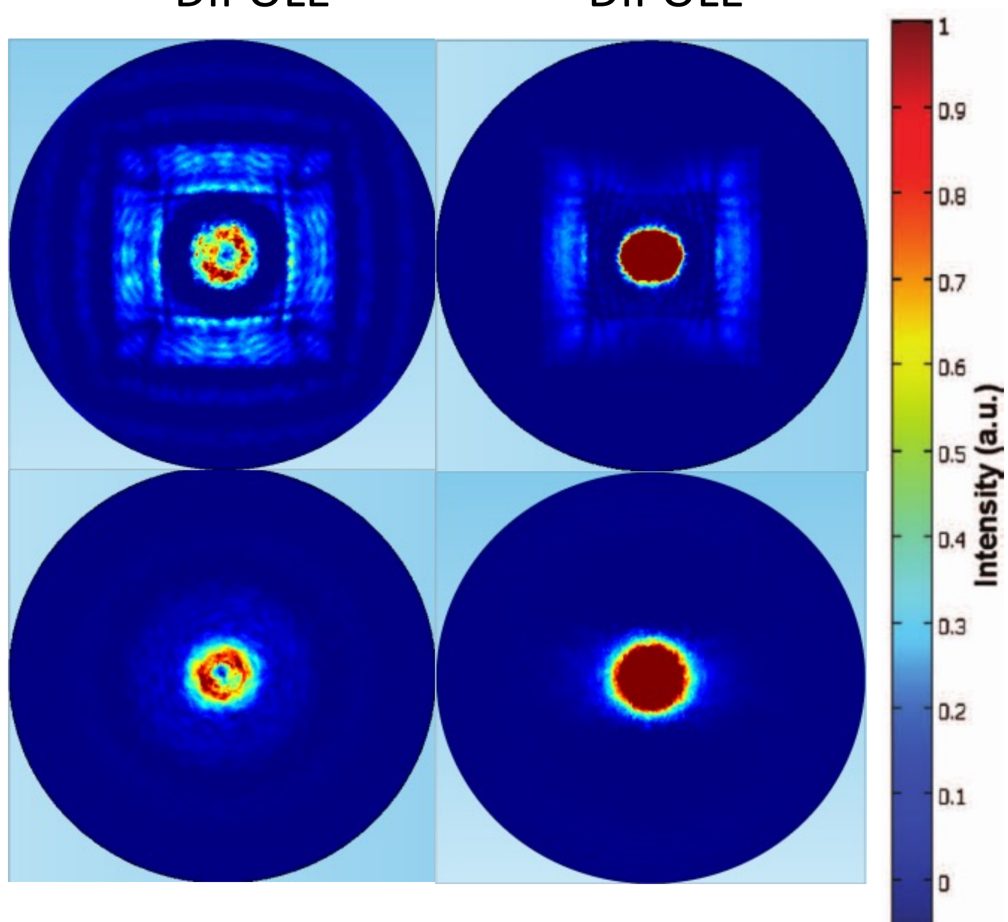
Qu,et al., *Nature Photonics* (2015), **9**, 758

Emission field calculations

VERTICAL DIPOLE | HORIZONTAL DIPOLE

WITH GRID

WITHOUT GRID

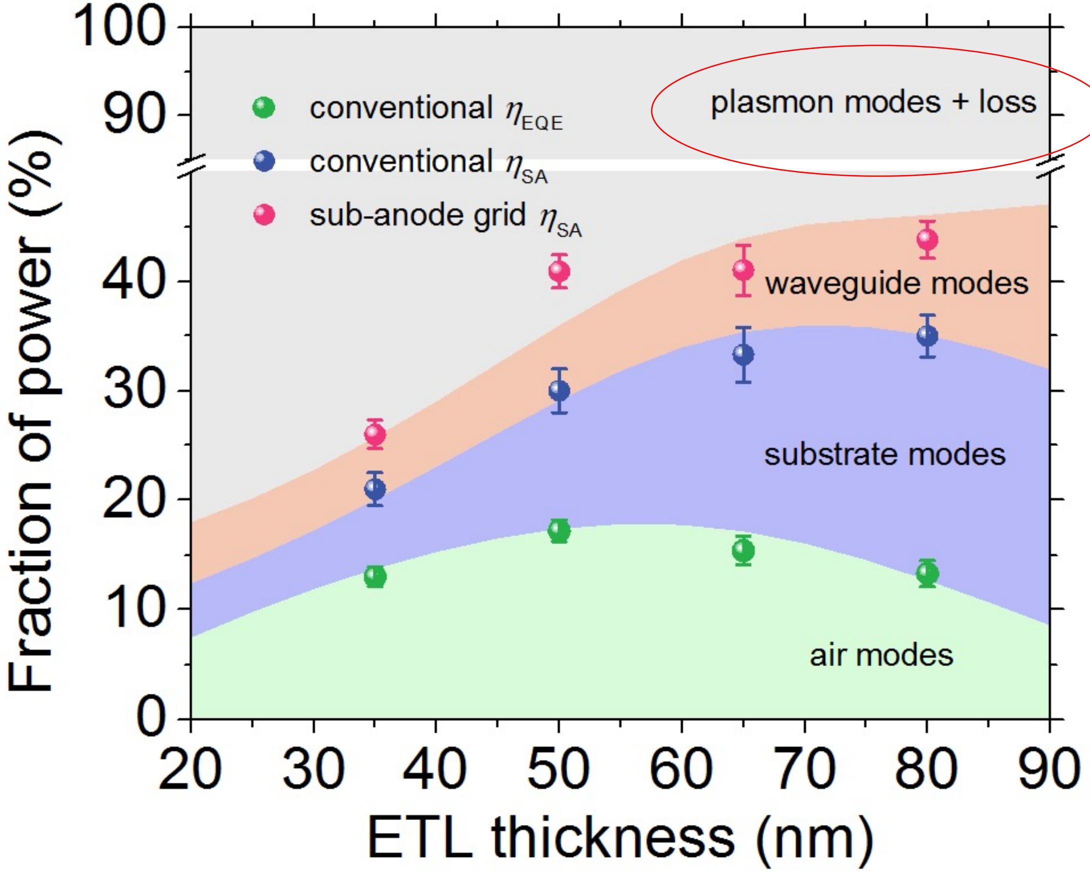


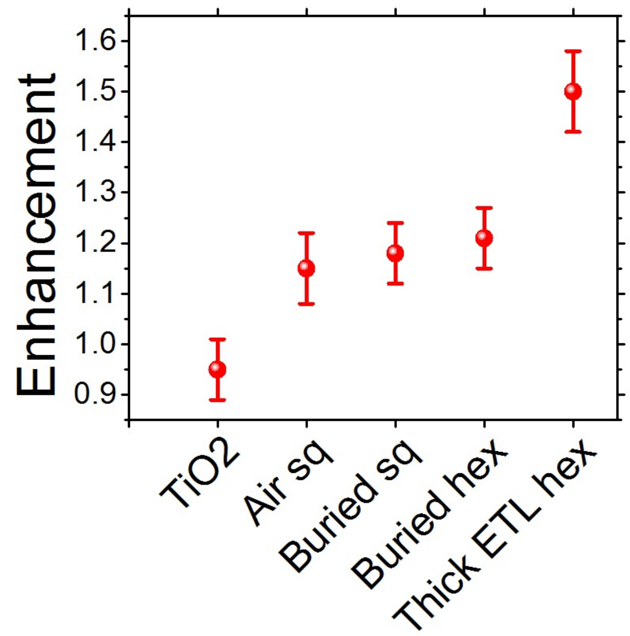
Mostly in-plane (Waveguided)

Mostly out-of-plane (Glass + air)

Qu,et al., *Nature Photonics* (2015), **9**, 758

Optical Power Distribution





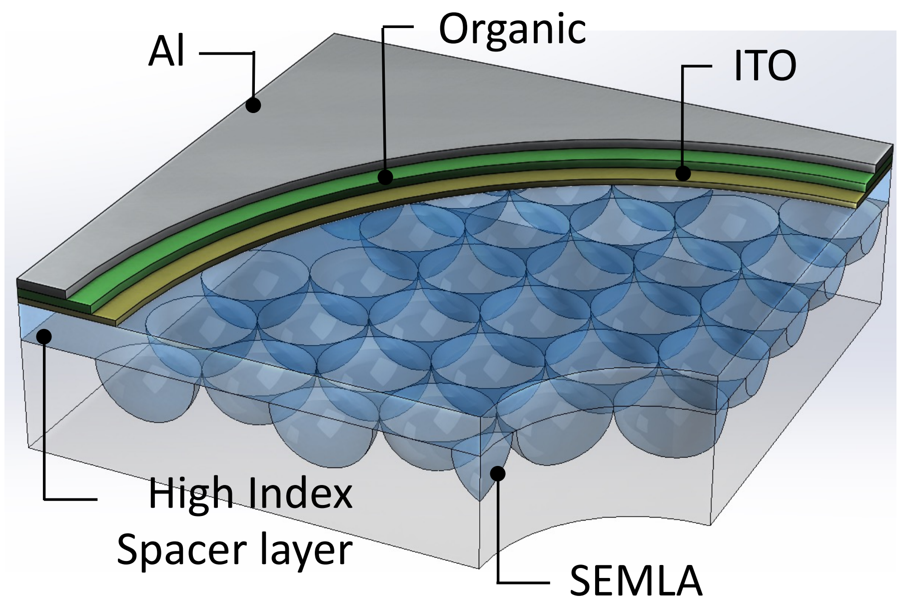
2nm MoO_3/40nm CBP/15nm CBP:$Ir(ppy)_3$/xnm TPBi/1nm LiF/Al

Thick-ETL organic structure:

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

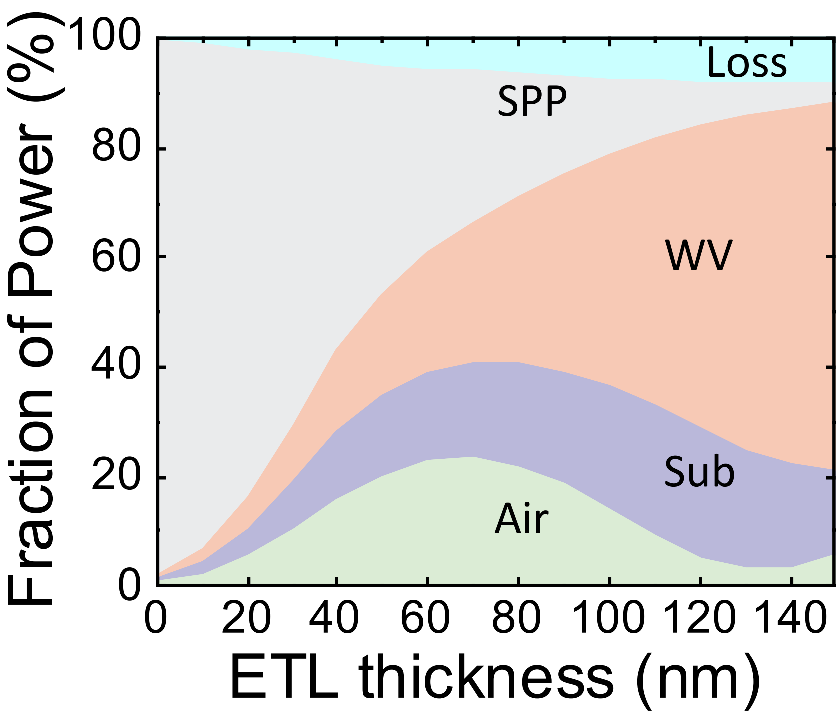
Qu,et al., *Nature Photonics* (2015), **9**, 758

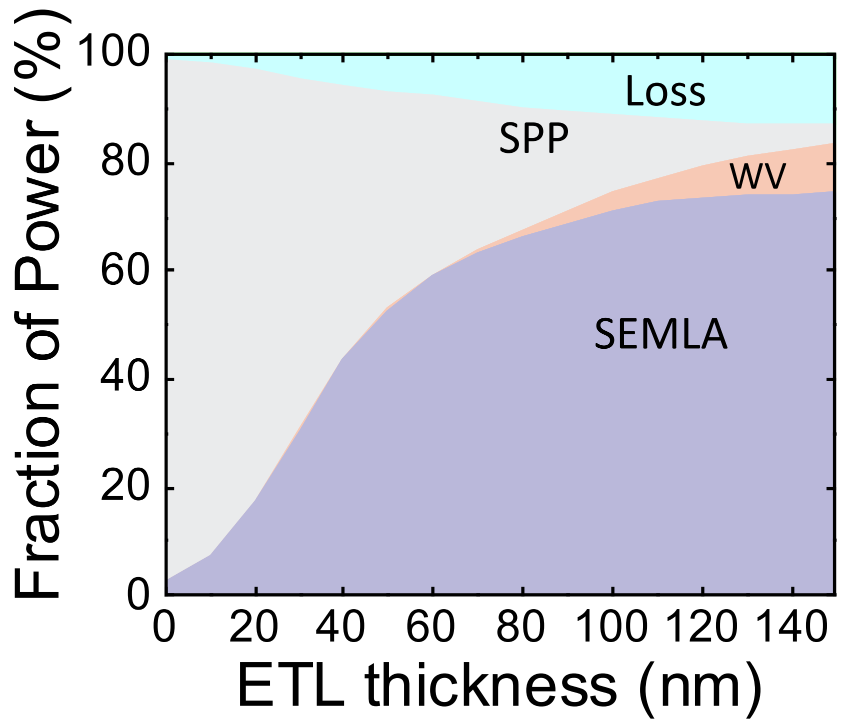
Getting All the Light Out: Sub-Electrode Microlens Array (SEMLA)



Qu, Y., et al. 2018. ACS Photonics, **5**, 2453.

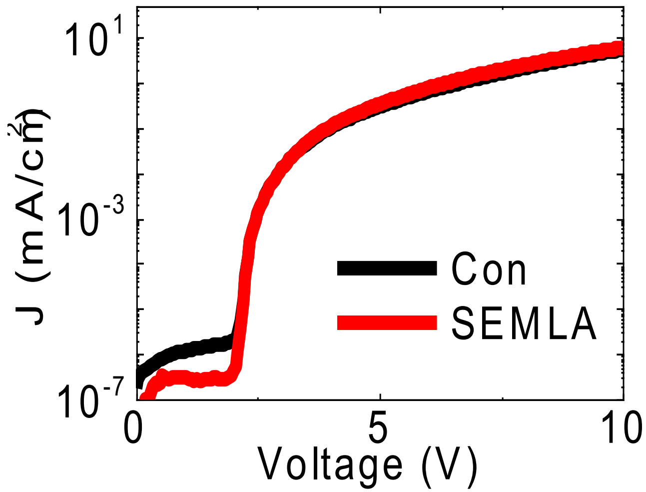
SEMLAs Change the Outcoupling Landscape

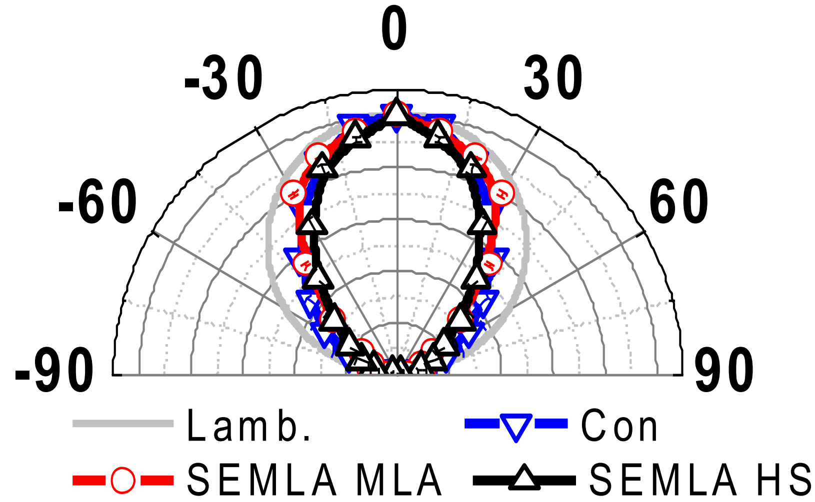


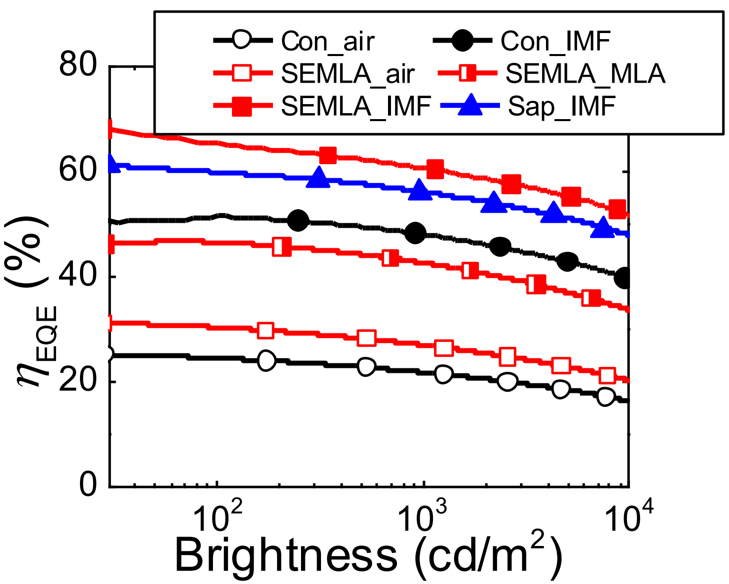


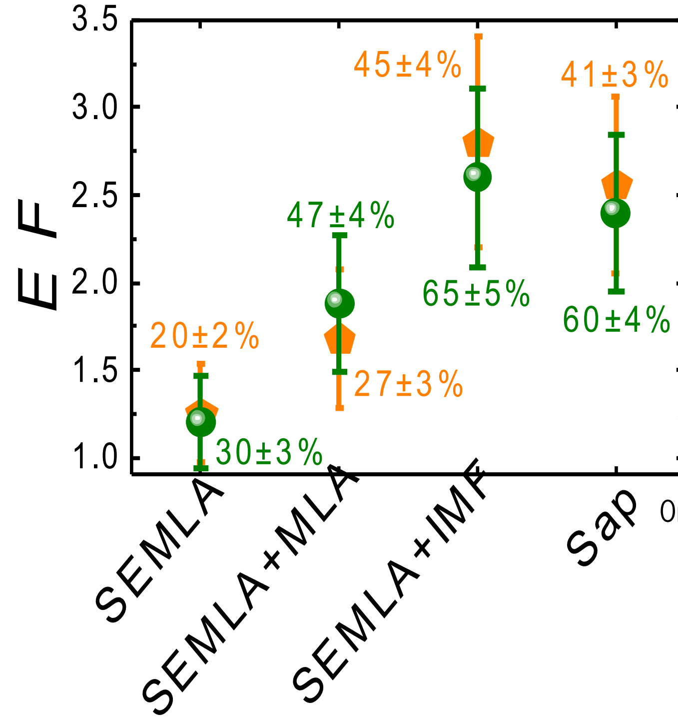
Qu, Y., et al. 2018. ACS Photonics, **5**, 2453.

SEMLA Performance



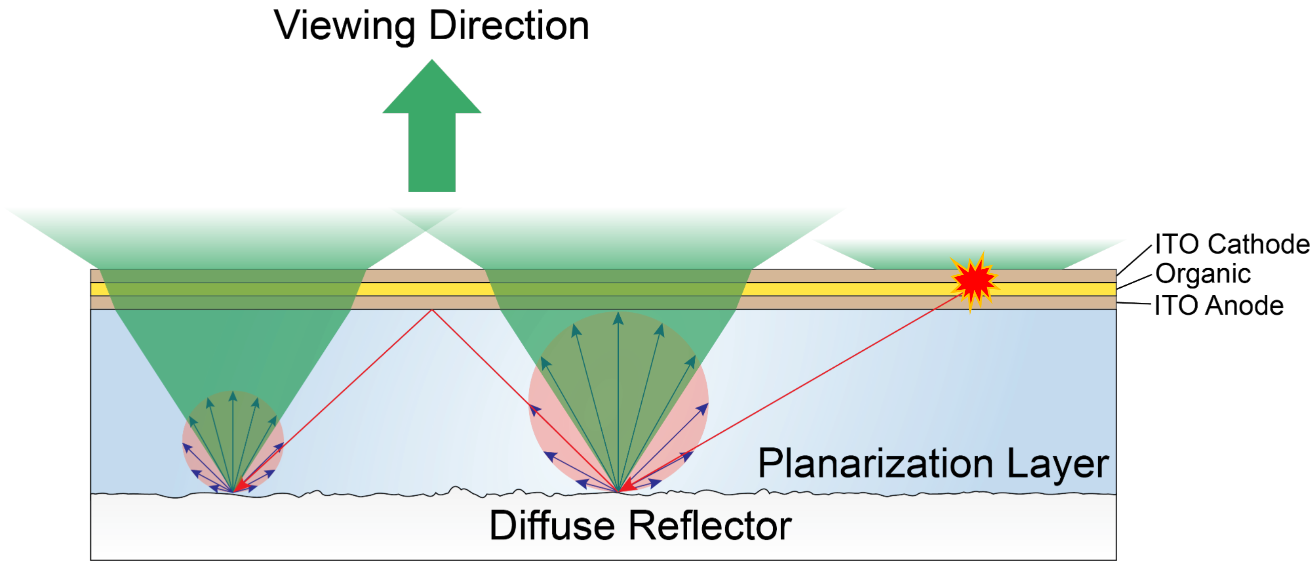




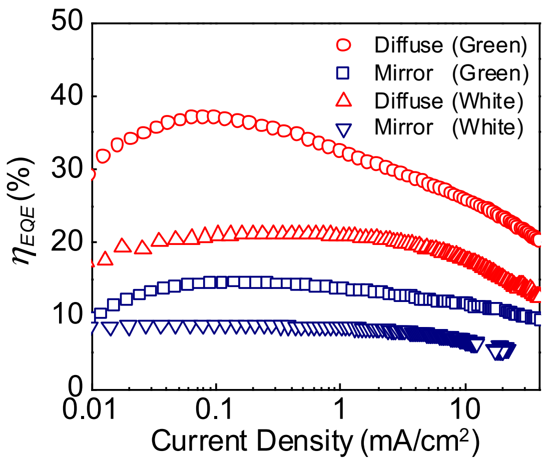


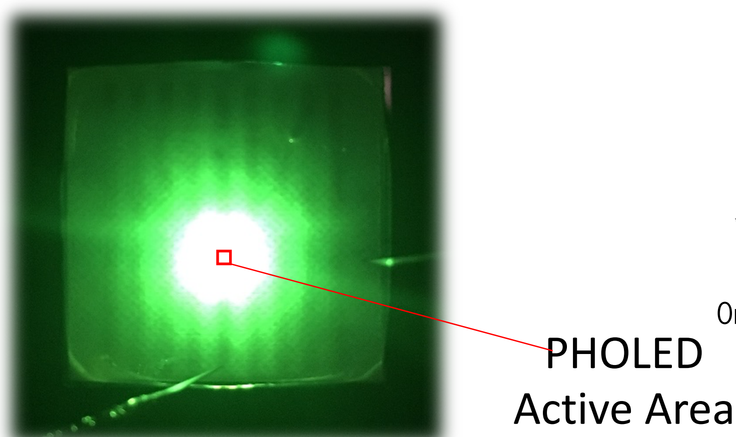
Qu, Y., et al. 2018. ACS Photonics, **5**, 2453.

Diffuse Reflectors: Low Cost & Simple



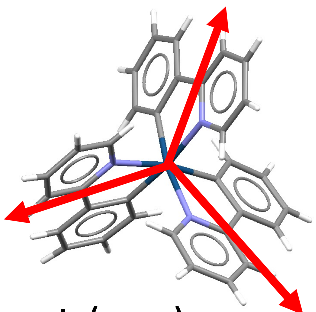
Teflon is the best diffuse dielectric reflector



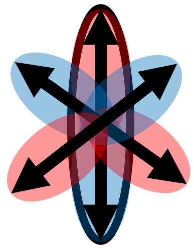


Kim, J., et al. (2018), ACS Photonics, **5**, 3315.

Outcoupling Enhancements by Molecular Orientation

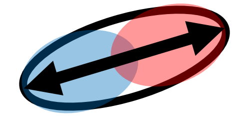


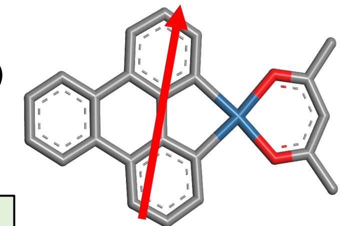
$Ir(ppy)_3$



Isotropic Orientation

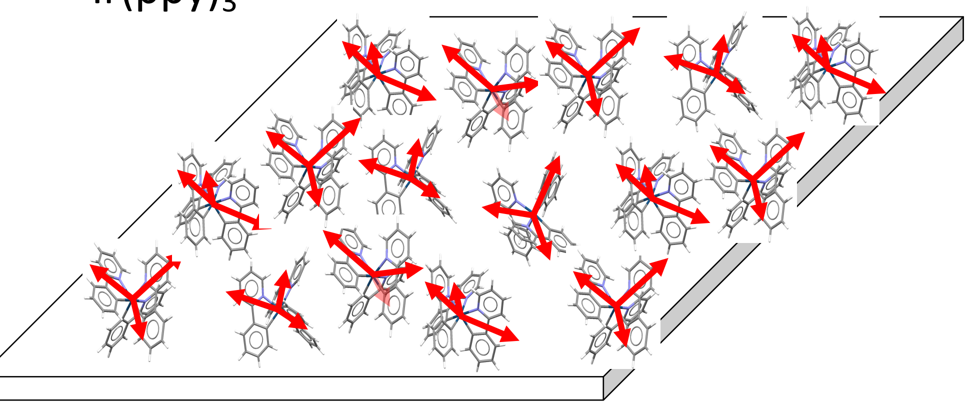
Horizontal Orientation

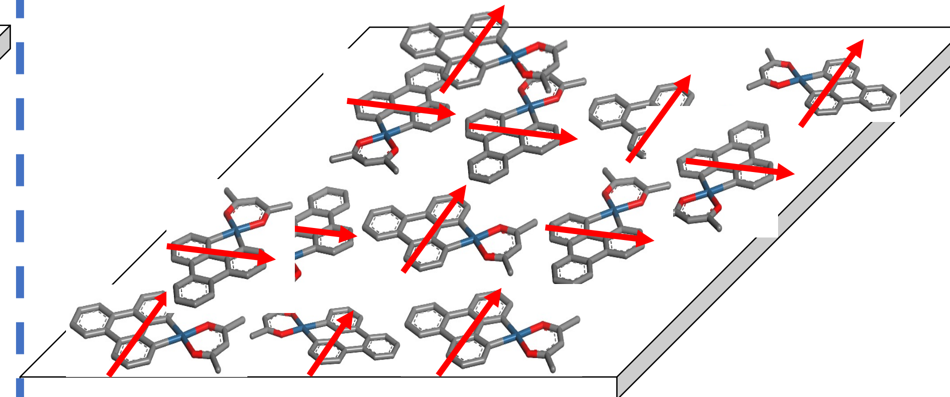


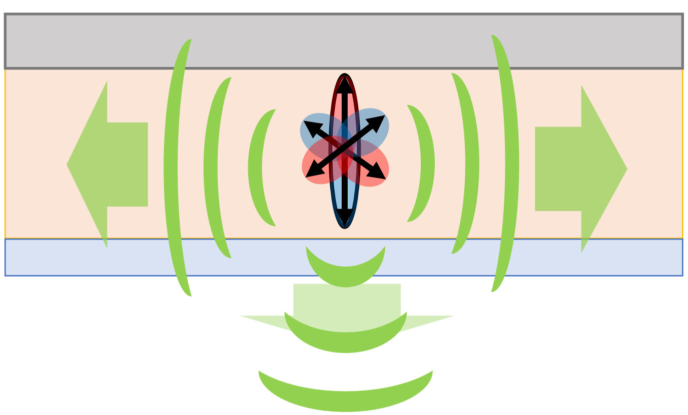


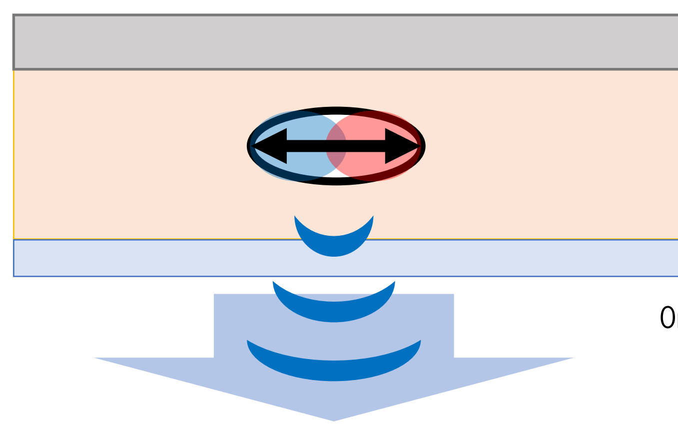
Prevents coupling to SPPs and waveguide modes

Pt(dbq)(acac)





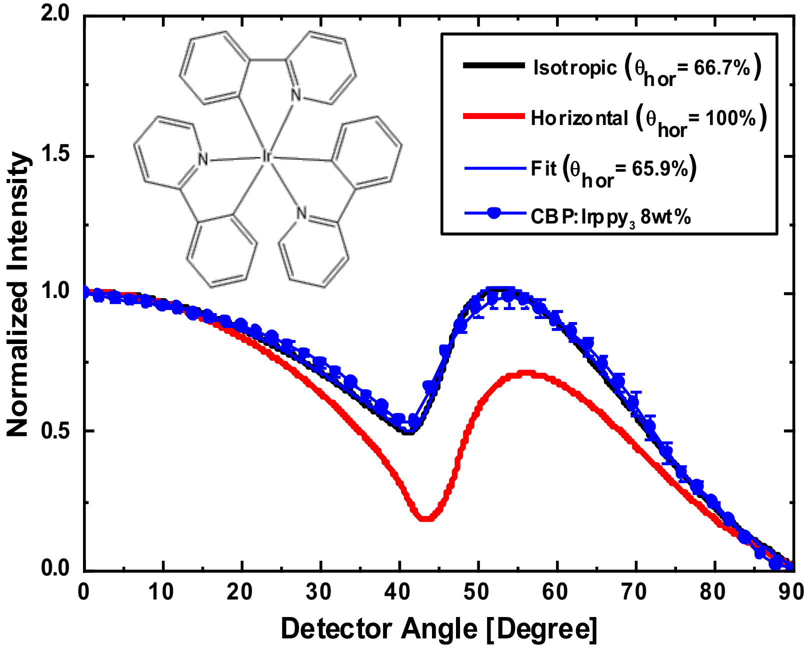




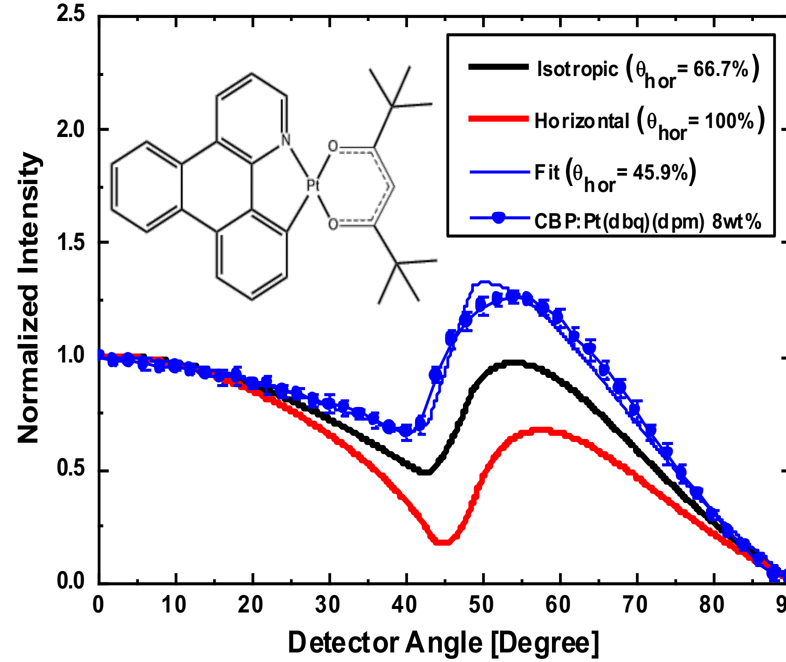
Planar molecules (e.g. Pt-complexes) more likely to align than octahedral (tris-Ir complexes)

Example results

Ir(ppy)$_3$



Pt(dbq)(dpm)



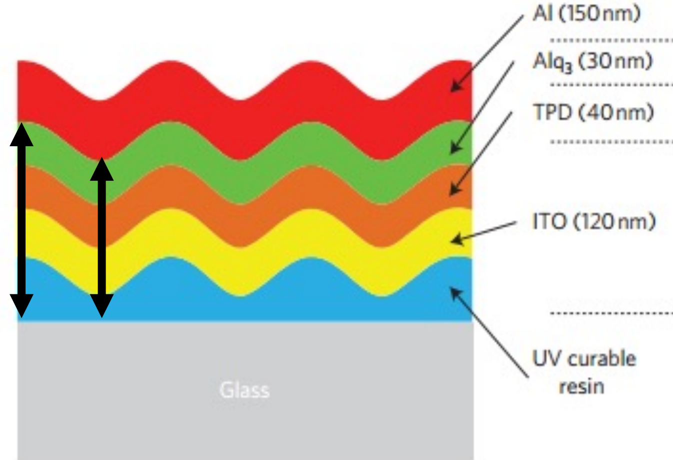
Ratio of light emitting by vertical to horizontal dipoles: $\Theta = \dfrac{TM_{\parallel}}{TE_{\perp} + TM_{\perp} + TM_{\parallel}}$

<u>Approach challenges</u>

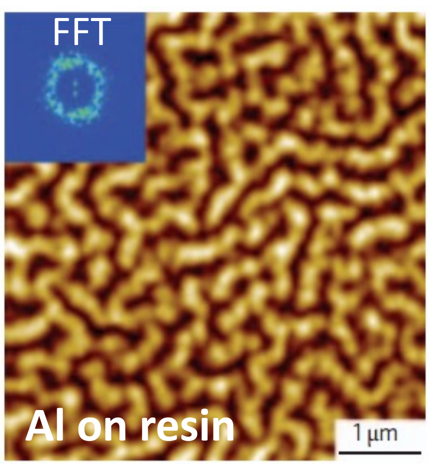
- Added constraints on molecular design
- Added constraints on process (growth) conditions: may not align as expected
- Added constraints on device architecture
- Alignment is never "perfect": only modest improvements

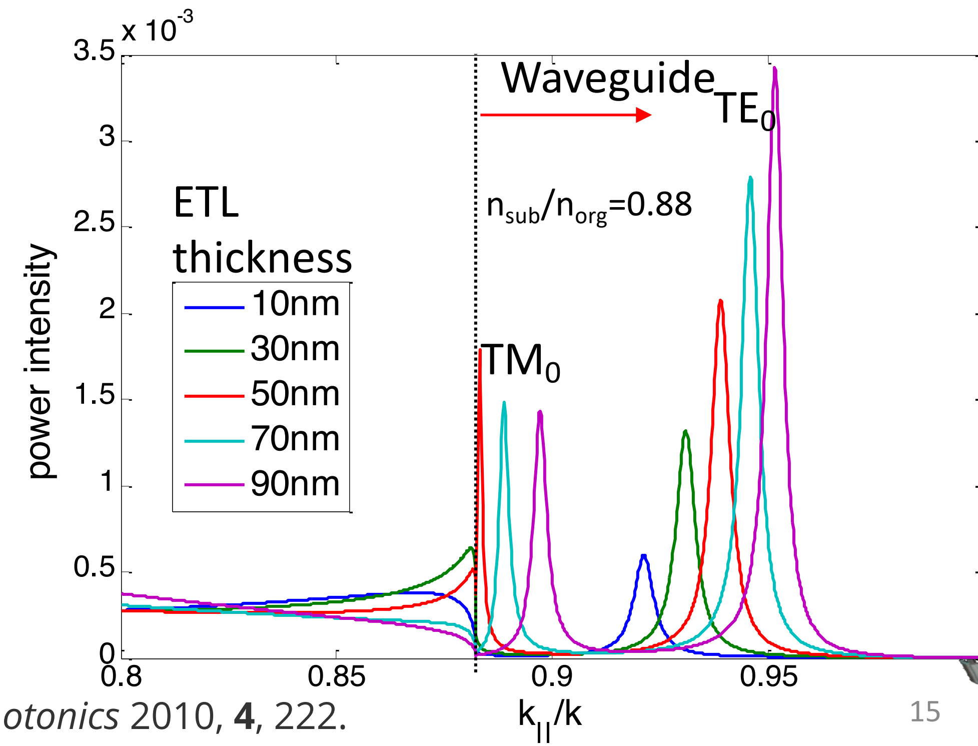
Substrate Corrugations Can Outcouple Waveguide Modes

- Waveguide thickness varies due to the corrugation.
- As the thickness changes, the mode distribution changes.
- When the waveguided power travels from thin to thick areas, the k vector needs to change direction to keep "being trapped". Otherwise, the light is extracted.



A possible approach: Surface buckling?





W. H. Koo, et al, *Nat. Photonics* 2010, **4**, 222.

Reliability Testing Methodologies

- Need to set clear metrics for failure
  - Example: Operating time for initial luminance (L_0) to decrease 10% from its initial value (called T90, or LT90)
  - Employ a population of equivalent devices and monitor their performance parameter (e.g. luminance) under normal operating conditions
  - If degradation slow, then an empirical degradation relationship is determined to extrapolate time to failure
    - Example: **Stretched exponential function**:

$$L(t) = L_0 exp(-t/\tau)^{\beta}$$

τ, β = empirical constants

- If degradation too slow, need to accelerate via increased T or L_0.
  - Accelerated conditions must not introduce new failure modes
  - Need empirical relations to normalize lifetime to standard operating conditions (called **acceleration factors**)

$$LTx(L_0) = LTx(L_{0tst}) \bullet \left[\frac{L_{0tst}}{L_0}\right]^n$$

n = empirical acceleration factor

Accelerated Degradation Methodologies

Sum of lifetimes alternative empirical relation):

Burn-in — Long term decay

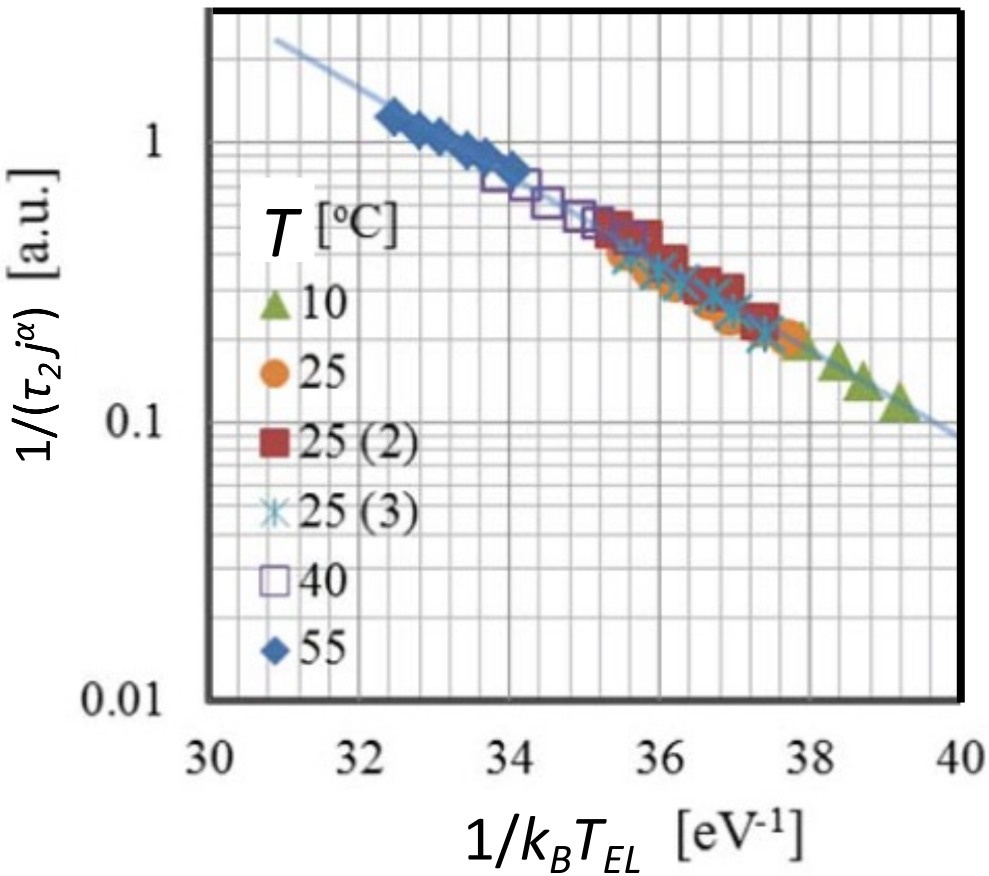
$$L(t)/L_0 = \lambda \exp(-t/\tau_1) + (1-\lambda)\exp(-t/\tau_2)$$

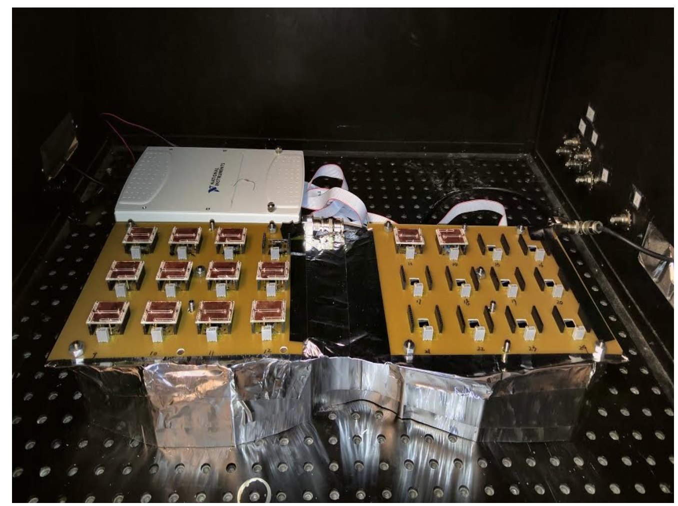
$$\frac{1}{\tau_2} = K'' j^{\alpha} \exp(-\Delta E_{A0}/k_B T)$$

ΔE_{A0}=thermal activation of degradation

α = current acceleration factor

Example data: Green PHOLED

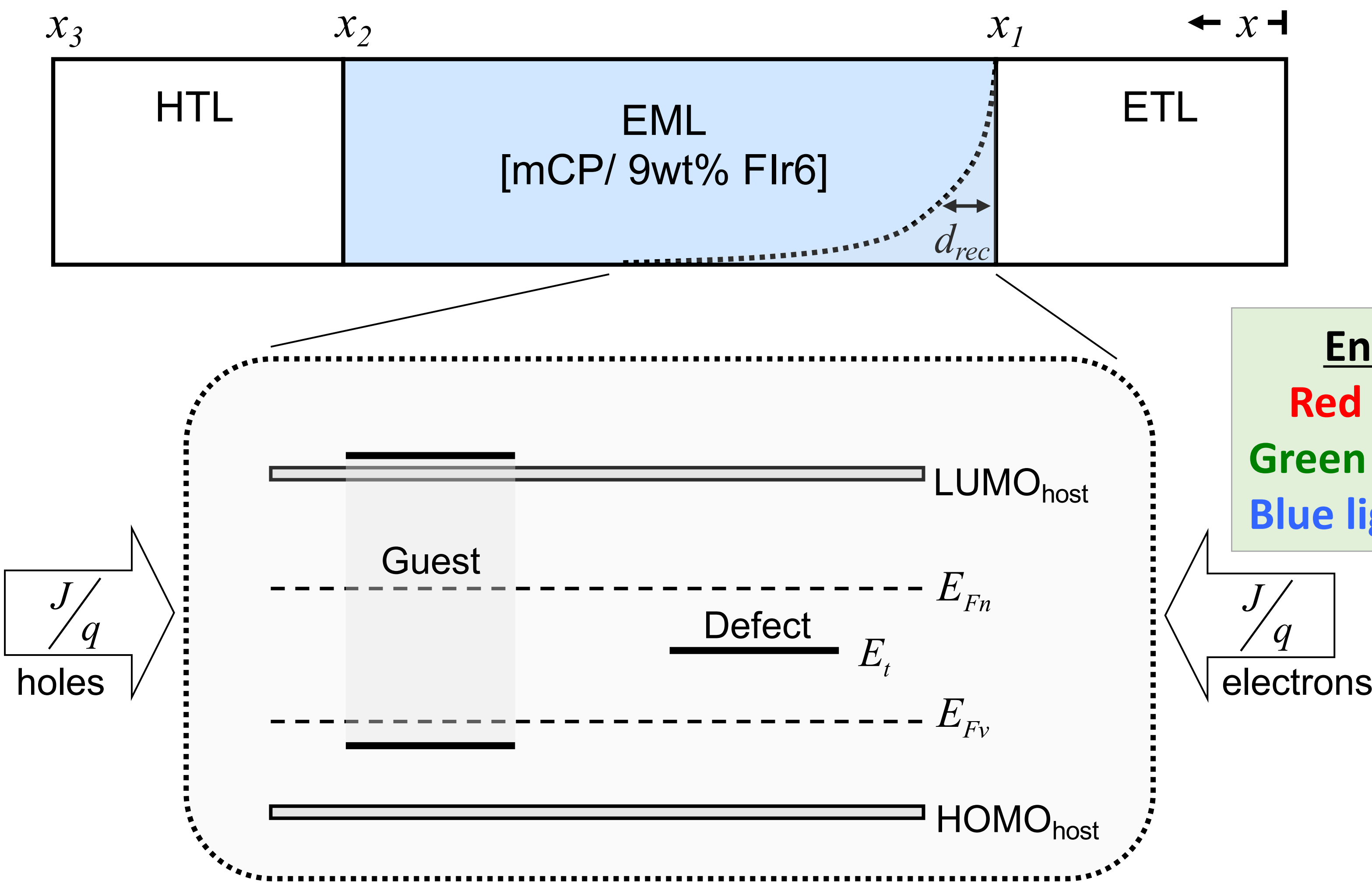




Measuring populations of identical devices

Yoshioka, et al.. 2014,*SID Digest Tech. Papers,* 45**,** 642.

Intrinsic Lifetime Limits of OLEDs



Energy Scale

Red light: ~ 2 eV

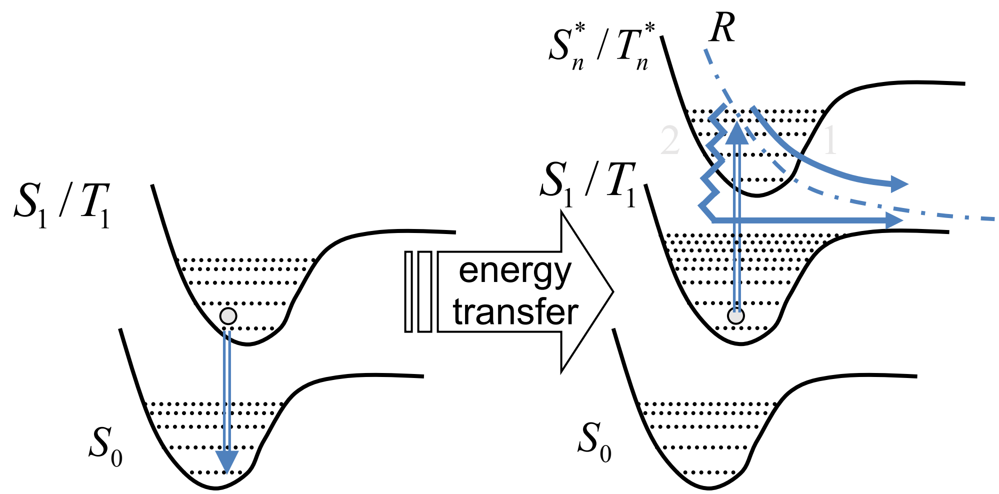
Green light: ~2.3 eV

Blue light: ~ 2.9 eV

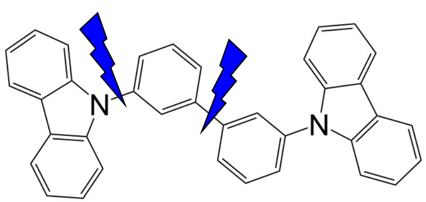
Giebink, et al., *J. Appl. Phys.*, **103**, 044509 (2008).

Degradation Routes

- Energetically Driven
  - Lifetime: R>G>B
- Two particle interactions lead to luminance loss
  - Exciton on phosphor, polaron on host
  - Exciton-exciton also possible

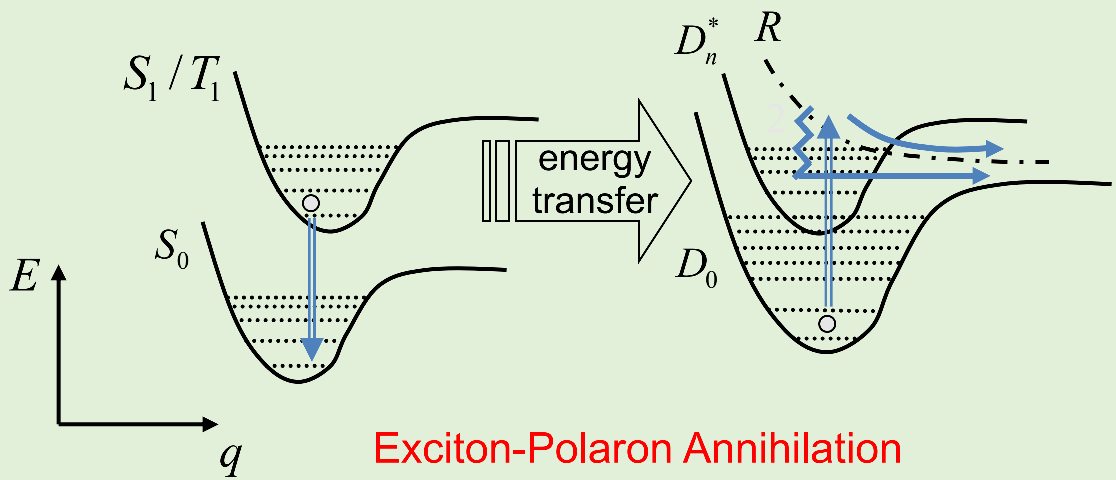


Exciton-Exciton Annihilation



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!

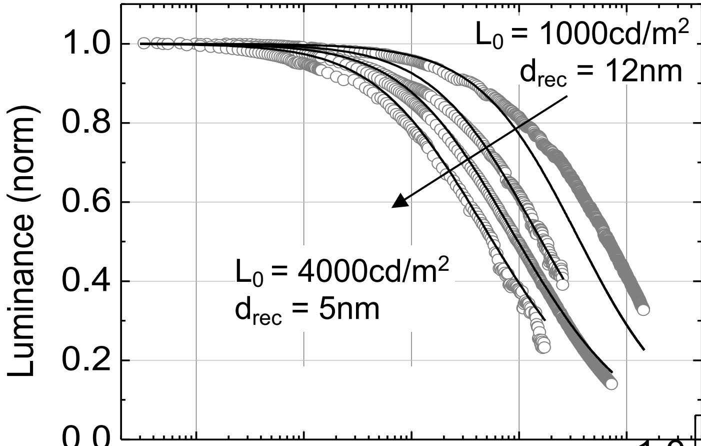


Exciton-Polaron Annihilation

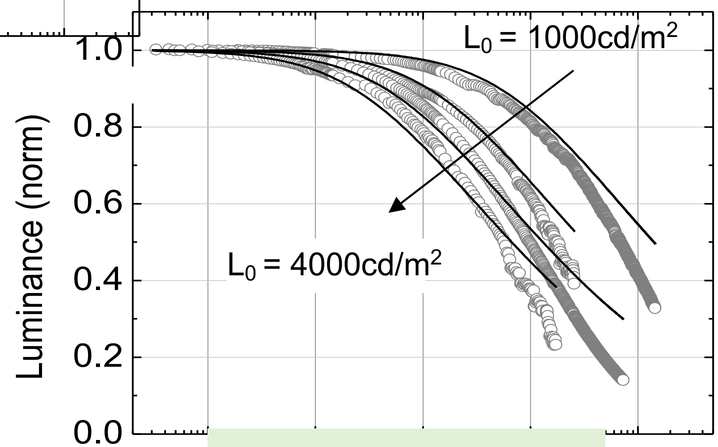
Triplet energy (~2.8 eV) + polaron (~3.3 eV) = hot polaron (≥ 6 eV)

Luminance Decay vs Time

- Blue PHOLED
- Prepared and packaged using industry std.

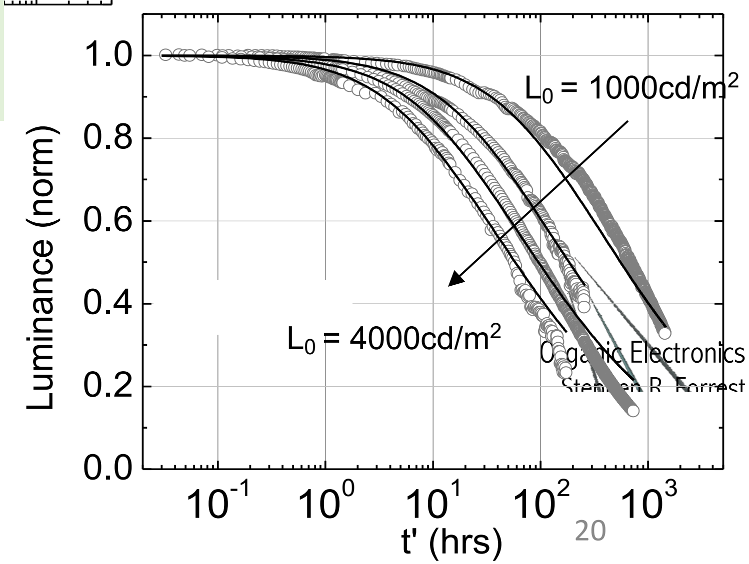


Exciton Localization



Exciton-Exciton Annihilation

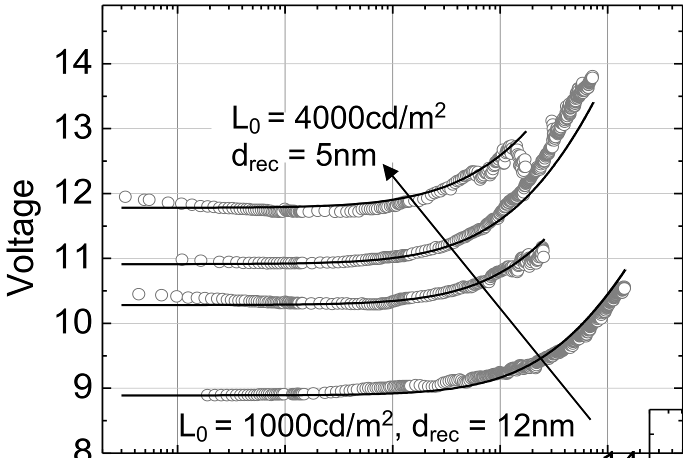
Exciton-Polaron Annihilation



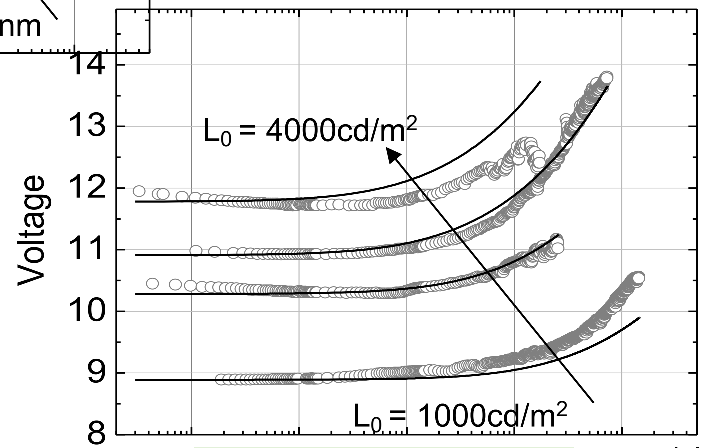
Defect Generation Rates

$$\frac{dQ(x,t')}{dt'} = \begin{cases} K_X n(x,t') \quad K_X p(x,t') & \text{P} \\ K_X N(x,t') & \text{E} \\ K_X N^2(x,t') & \text{E-E} \\ K_X N(x,t') n(x,t') \quad K_X N(x,t') p(x,t') & \text{E-P} \end{cases}$$

Drive Voltage Drift with Aging

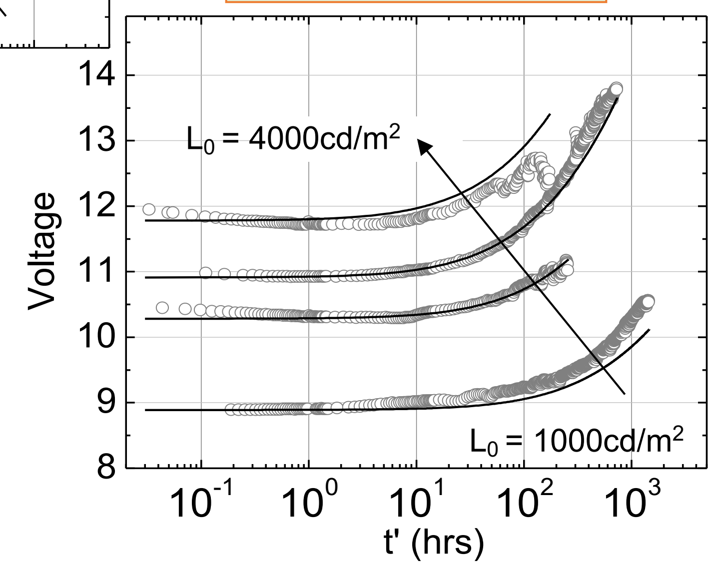


Exciton Localization



Exciton-Exciton Annihilation

Exciton-Polaron Annihilation

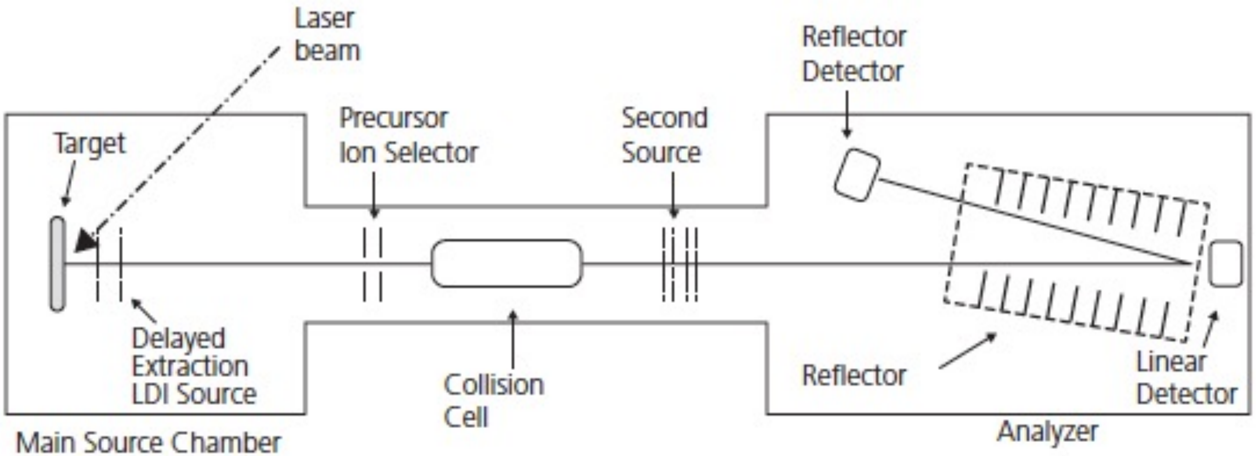


Conclusions

- Q~10^{18} cm^{-3} → 50% increase in quenching
- At 1000 cd/m^2, formation rate = $10^{12} cm^{-2}s^{-1}$
  - -1 in 5 x10^8 E-P encounters leads to defect
  - -Increasing recombination zone width extends lifetime
  - - Guest triplets/host polarons most active

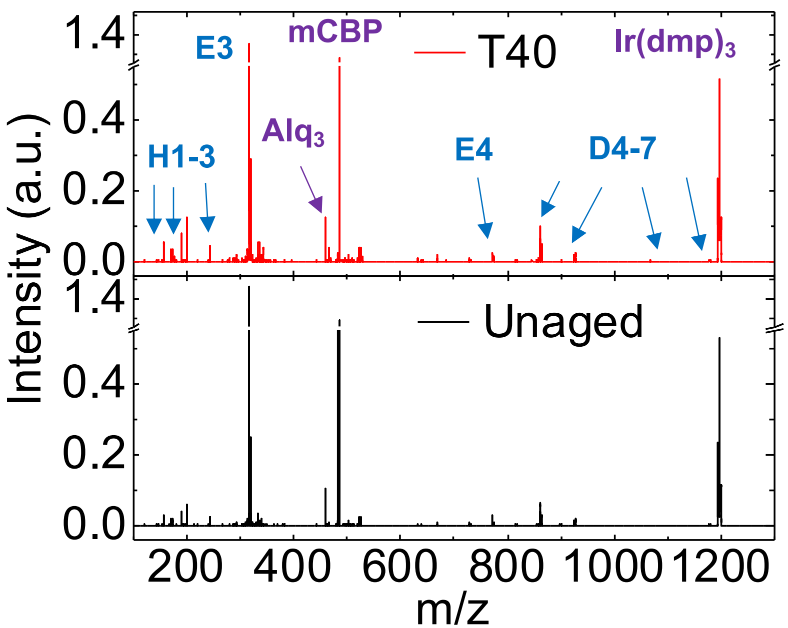
Giebink, et al., *J. Appl. Phys.*, **103**, 044509 (2008).

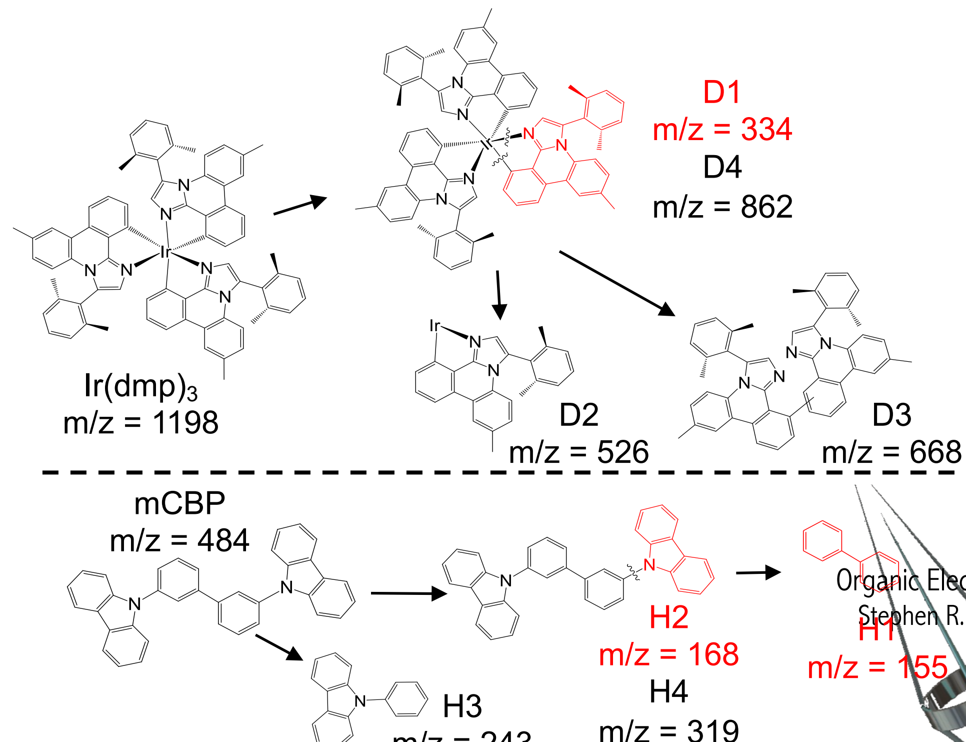
Evidence for Defect Formation: Molecular Fragmentation



Laser Desorption Ionization-Time of Flight Mass Spectroscopy (LDI-TOF-MS)

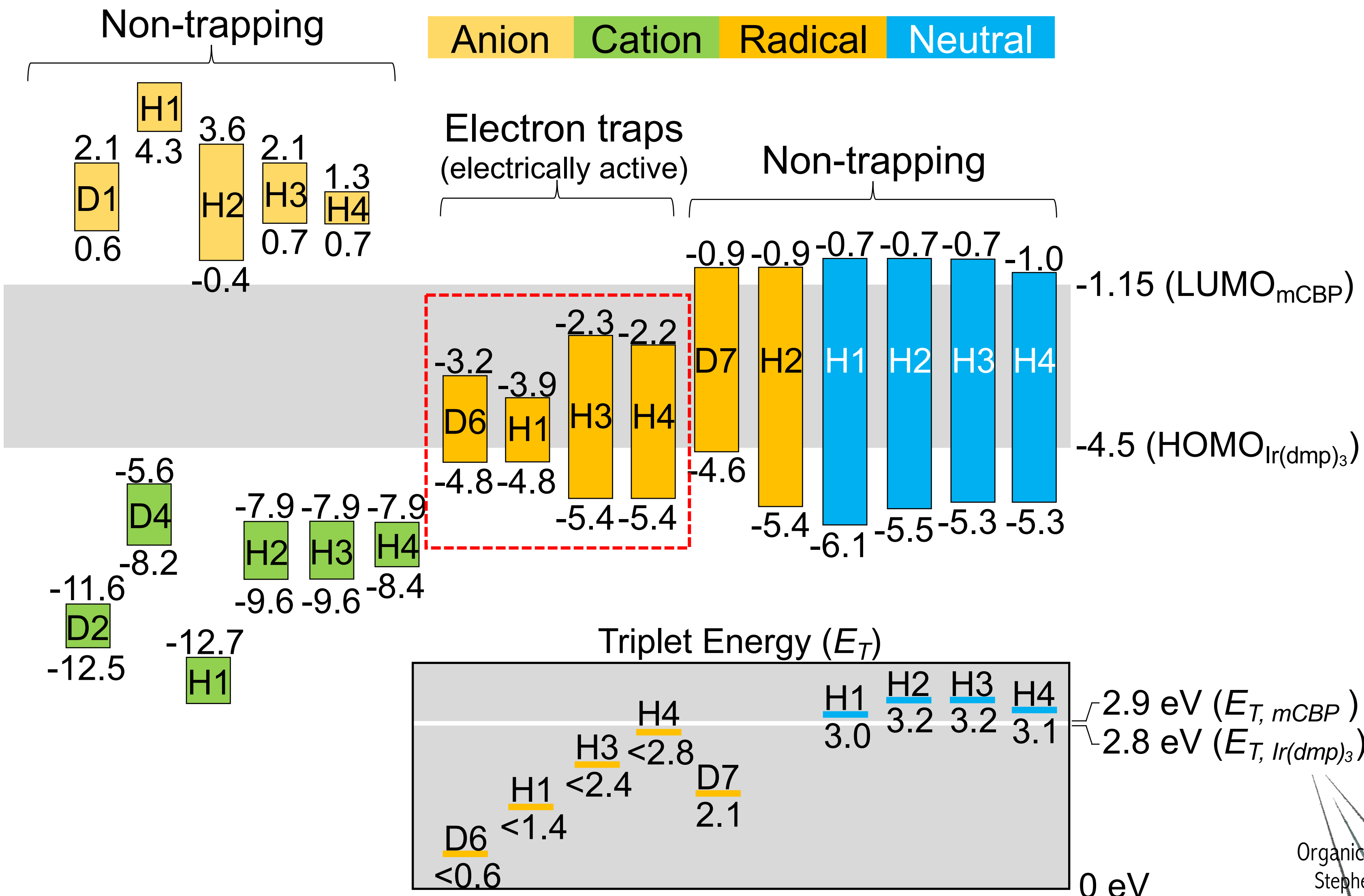
-Molecular species identification





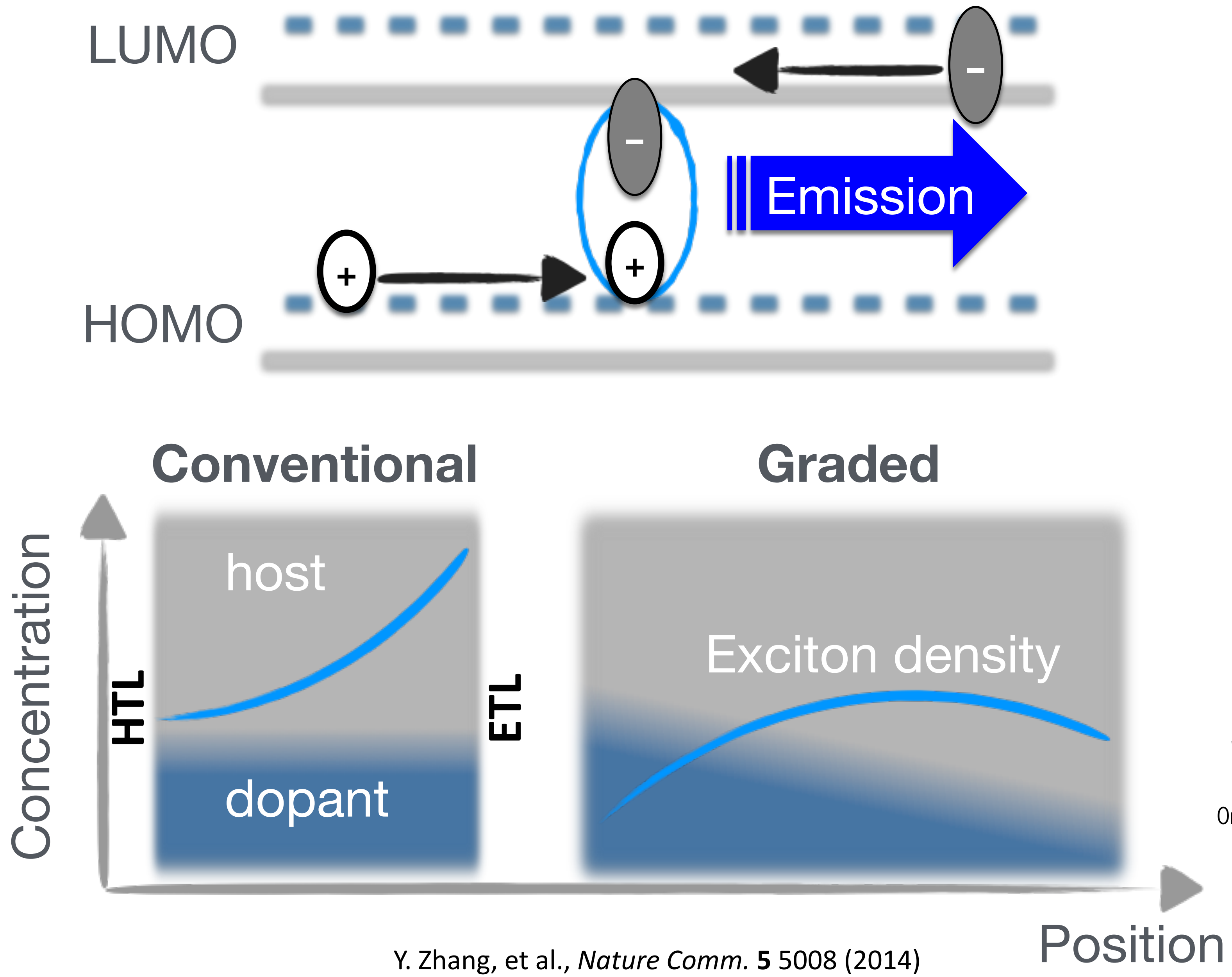
Jeong, et al. Org. Electron., **64**, 15 2019

Identification of Defect Energies

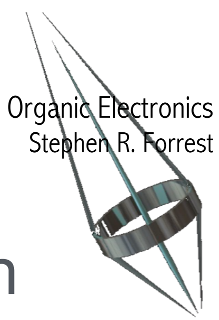


Jeong, et al. Org. Electron., **64**, 15 2019

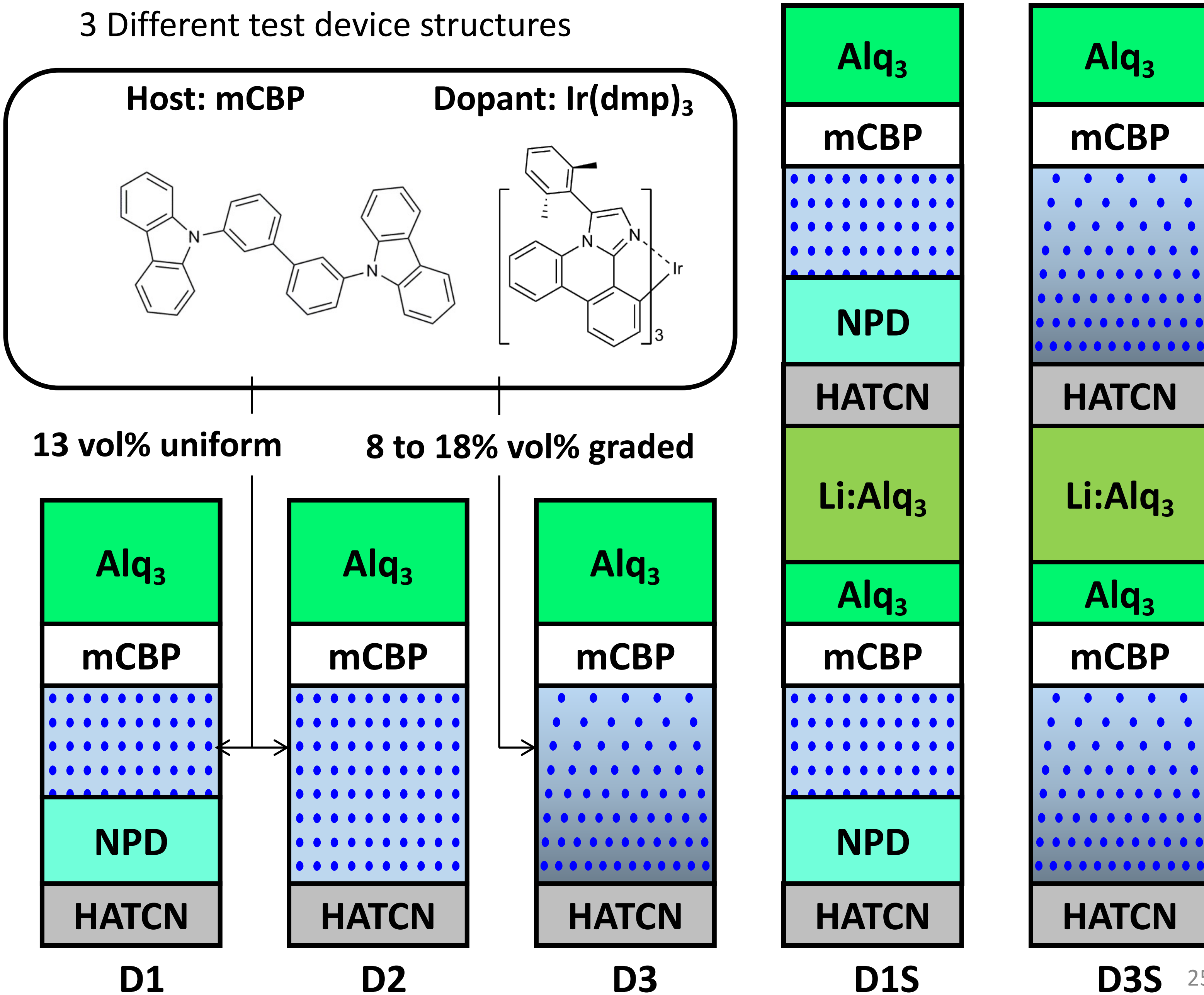
Reducing Exciton Density to Increase Lifetime



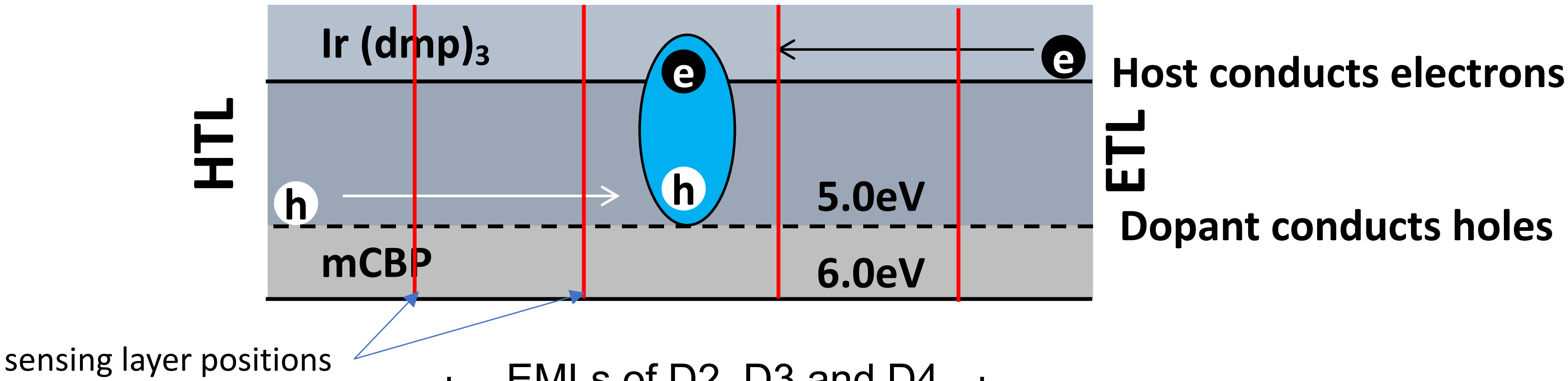
Y. Zhang, et al., *Nature Comm.* **5** 5008 (2014)

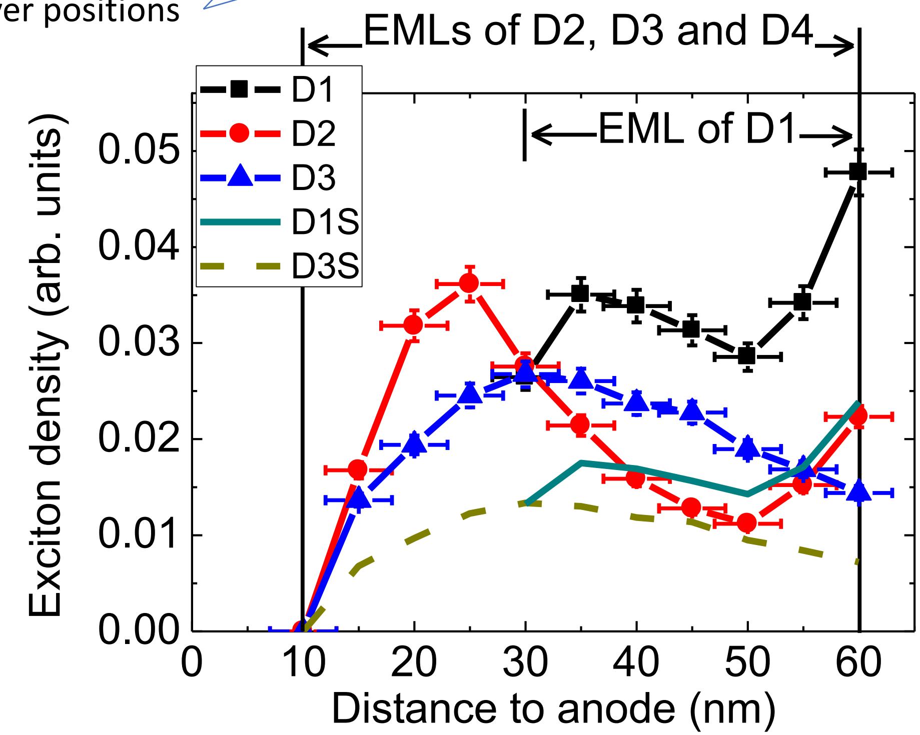


Spreading the recombination zone: Dopant/Host Grading



Excitons in the EML





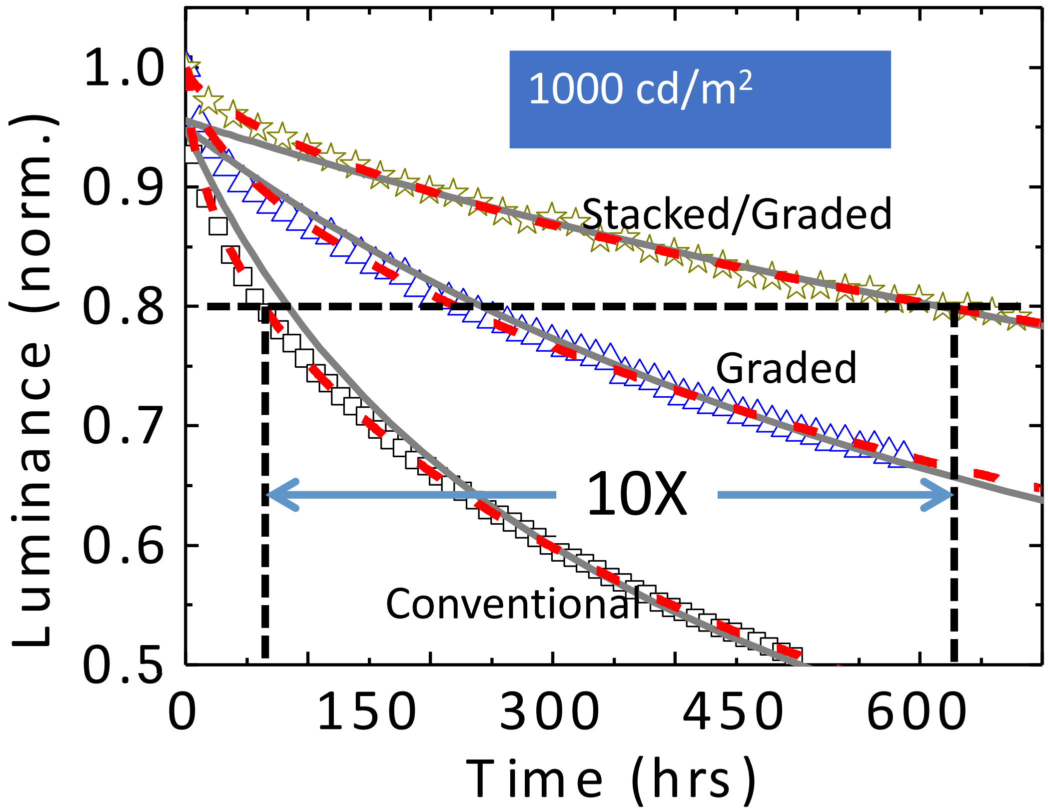
Exciton Sensing

- Red Phosphor (PQIr)
- 1.5 nm thick
- Placed at 5 nm intervals in EML
- Measure red emission intensity

Organic Electronics
Stephen R. Forrest

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

10 X Lifetime Improvement Over Conventional



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

Stacking is essential!

Panel 15 cm x 15 cm 82% fill factor	**2 Unit WSOLED**
Luminance [cd/m²]	**3,000**
Efficacy [lm/W]	**48**
CRI	**86**
Luminous Emittance [lm/m²]	7,740
1931 CIE	(0.454, 0.426)
LT_{70} [hrs]	**13,000**

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

Dopant Grading: Is it Good Enough?

using acceleration factors to predict lifetime

- Luminance to achieve sRGB color gamut for G is 10X that for B
- ⇒B sub-pixel L_0=100 cd/m^2 (c.f. G with L_0>1,000 cd/m^2)
- ⇒B lifetime to T50=70,000 hr.
- Adopting Degradation acceleration factor: n =1.55 with

$$T50(100\text{cd/m}^2) = T50(1000\text{cd/m}^2) \times \left[\frac{1000\text{cd/m}^2}{100\text{cd/m}^2}\right]^n$$

- ⇒B PHOLED lifetime to T50 = 1.3×10^5 hr.
- Commercial G PHOLED lifetime = 10^6 hours at L_0 = 1000 cd/m^2.

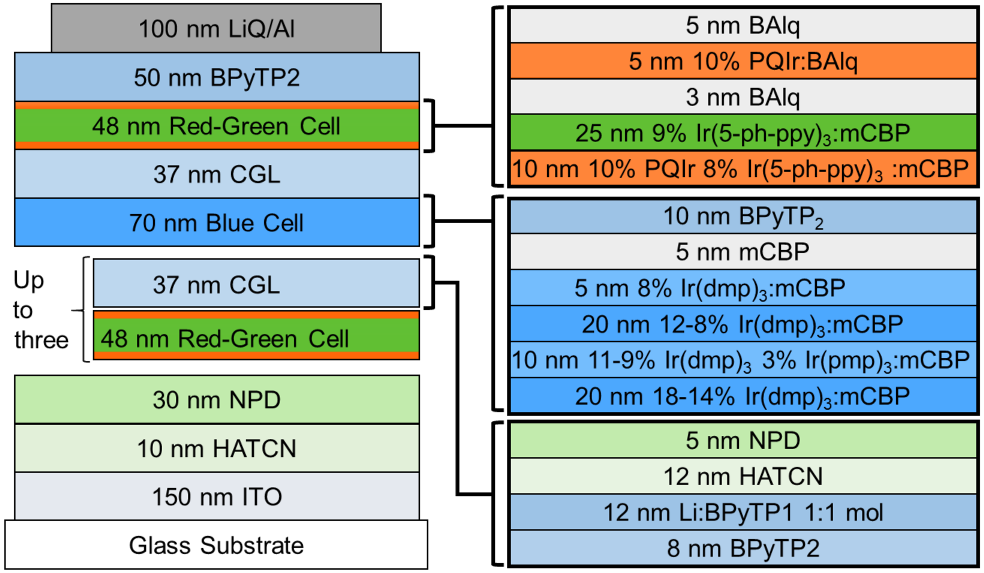
Not blue enough, T95 is required

Dopant Grading for Lighting: Is it OK?

- Current state of stacked WOLED: T70=13,000 hrs
- Mostly limited by blue lifetime
- Only light blue required
- Estimated increase in lifetime for stacked blue at lighting brightness: ~4X
- Lifetime of blue lighting using grading: 50,000 hr

This is almost good enough

Putting Grading Excited State Management to Work: Long lived all phosphor stacked WOLEDs



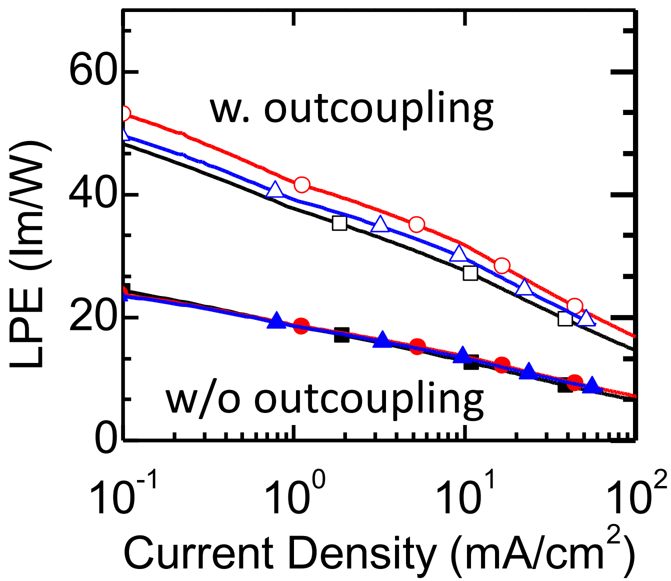
- Max Luminance > 200,000 nits
- 50 lm/W max
- CCT = 2780K
- CRI=89

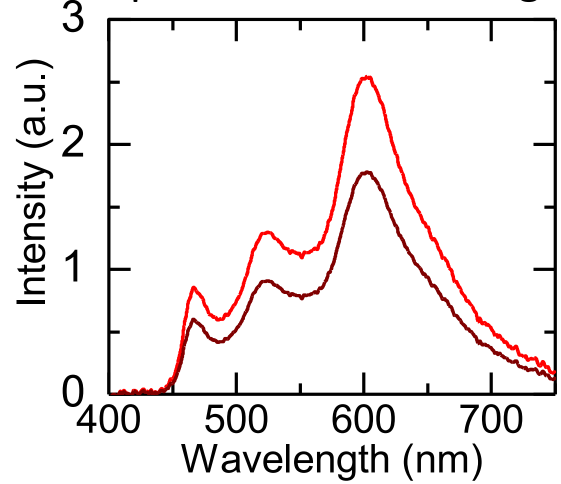
Photo illustrating good color rendering of the SWOLEDs in this report. The luminaire comprises 36 pixels (2 mm^2) operated at 50-100k nits

Electronics
...n R. Forrest

Coburn et al., ACS Photonics 5, 630 (2017)

All Phosphor SWOLED Performance

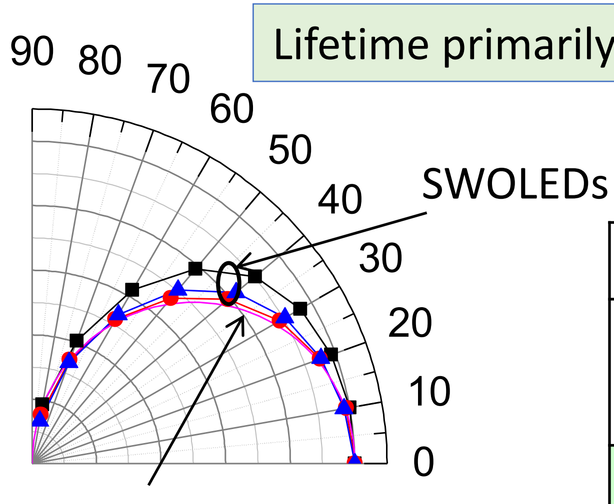




T70	SWOLED
ΔCCT	-360 K
ΔCRI	-0.8
ΔCIE	(0.03,0)

SWOLED Architecture	**Blue degradation @ WOLED T70:**
Conv	T28
Grad-Managed	T48

Lifetime primarily limited by R/G sections



	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%

Coburn et al., ACS Photonics 5, 630 (2017)

What we learned about OLEDs

- Chromaticity and the perception of color is quantified based on eye response (photometic quantities)
- OLEDs reach highest efficiency when both singlets and triplets are harvested (heavy metal complexes and TADF molecules)
- Optimized OLEDs have many layers serving purposes ranging from charge conduction, contacting to electrodes, to light emission
- Outcoupling methods essential to view substrate and waveguide modes while limiting surface plasmons
- Degradation of OLEDs particularly severe for blue due to bimolecular annihilation
- Lighting requires broad spectral emission using multilayer devices or excimer emission
- OLEDs provide uniform, area lighting vs. specular LED lighting