OLEDs for Lighting: How to Make Bright, Long-lived and Efficient Devices

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OLEDs: Major Remaining Challenges

- 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

Efficiency and Operational Lifetime of OLEDs & PHOLEDs

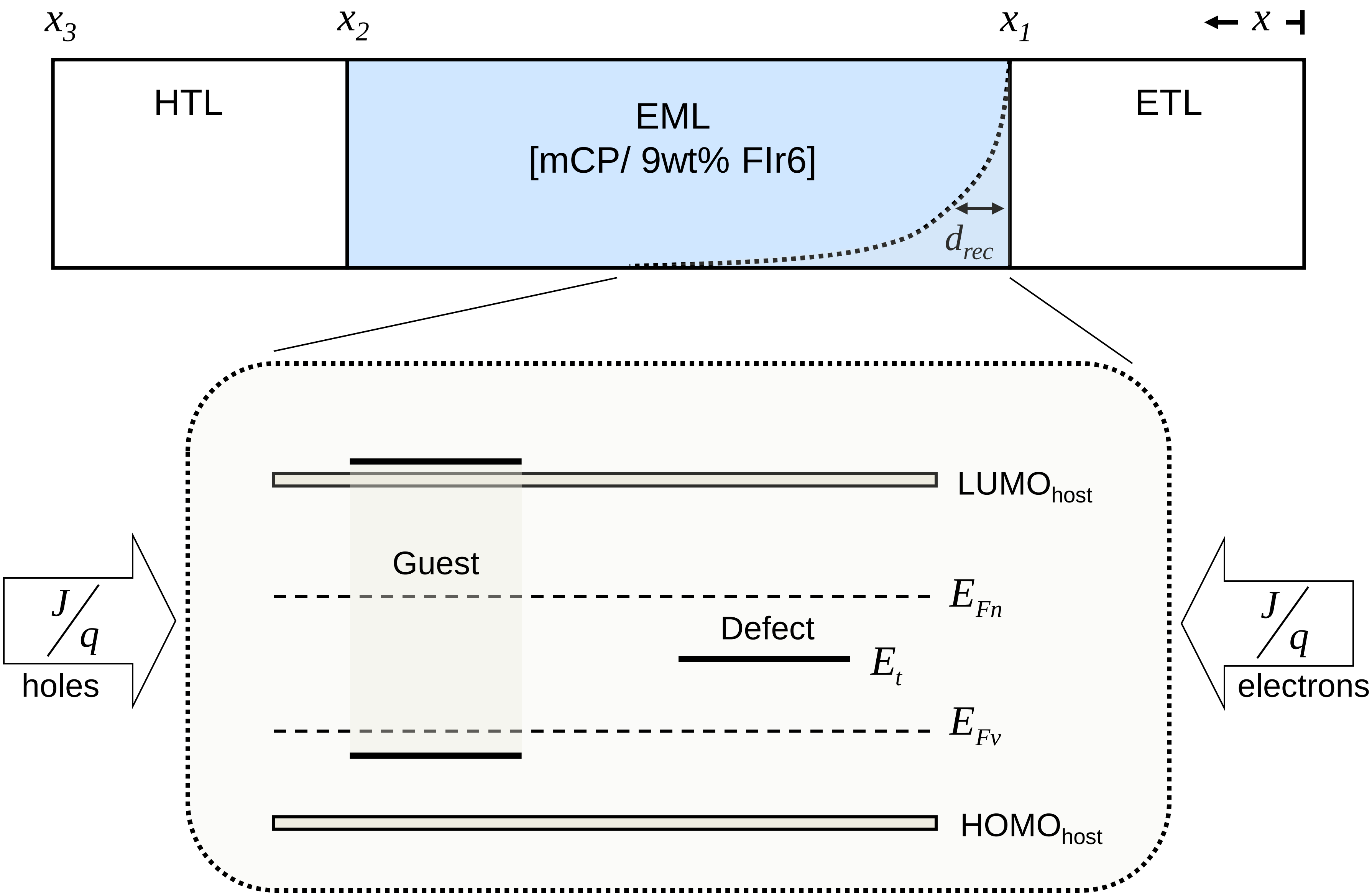
Phosphorescent dopants

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	**[0.14, 0.12]**	**High**	**100's**

Fluorescent 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**

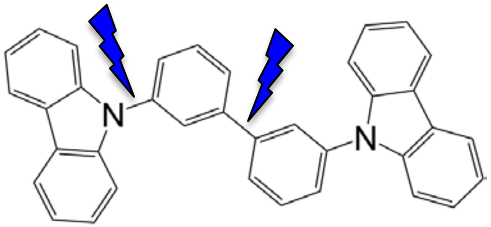
Intrinsic Lifetime of OLEDs



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

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

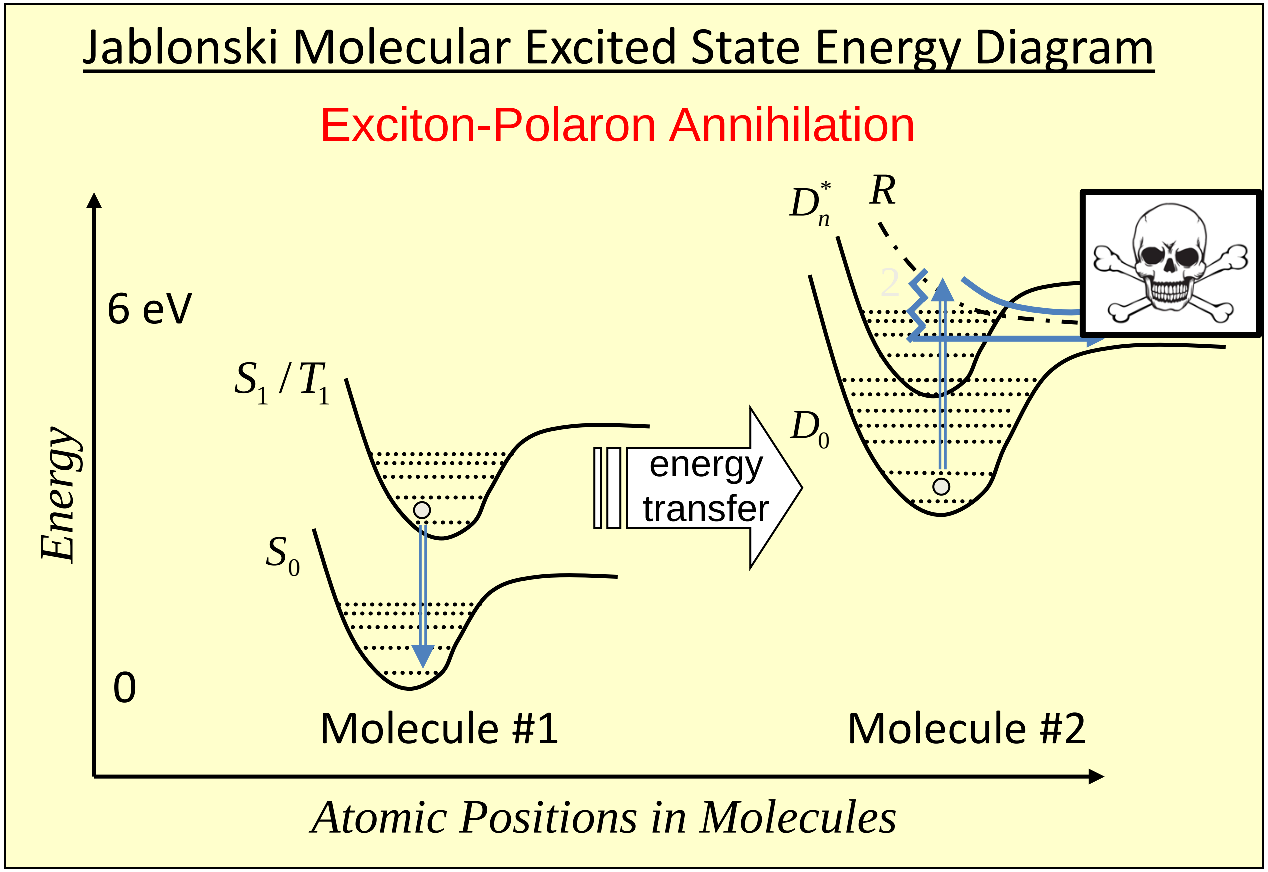
Red light: ~ 2 eV

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…



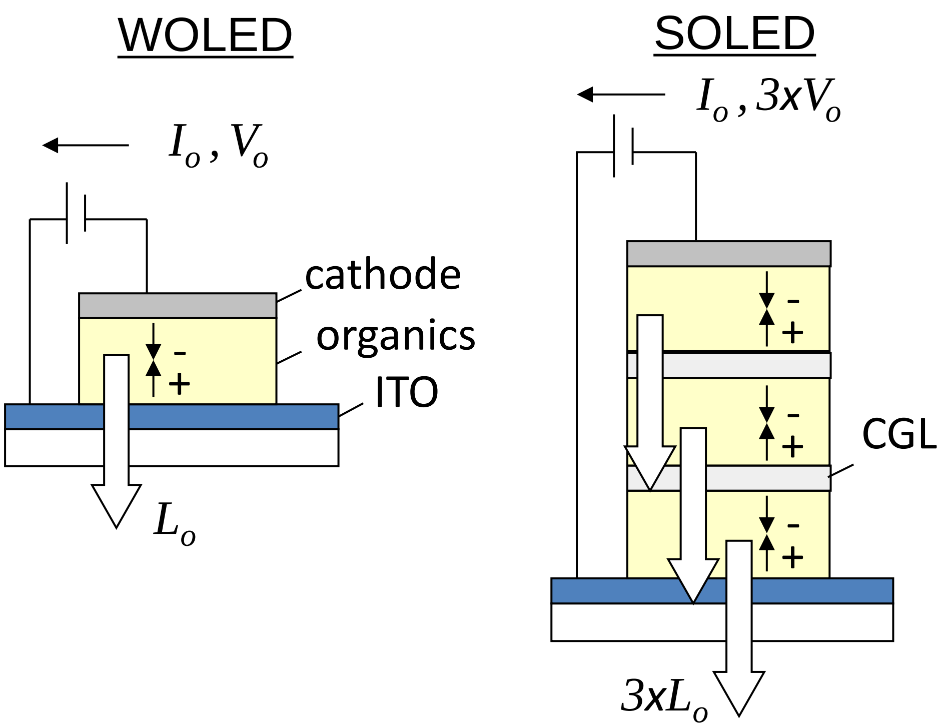
Triplet energy (~2.9 eV) + polaron (~3.3 eV) = hot polaron (≥ 6 eV)

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

WOLED vs. SOLED Lifetime Comparison

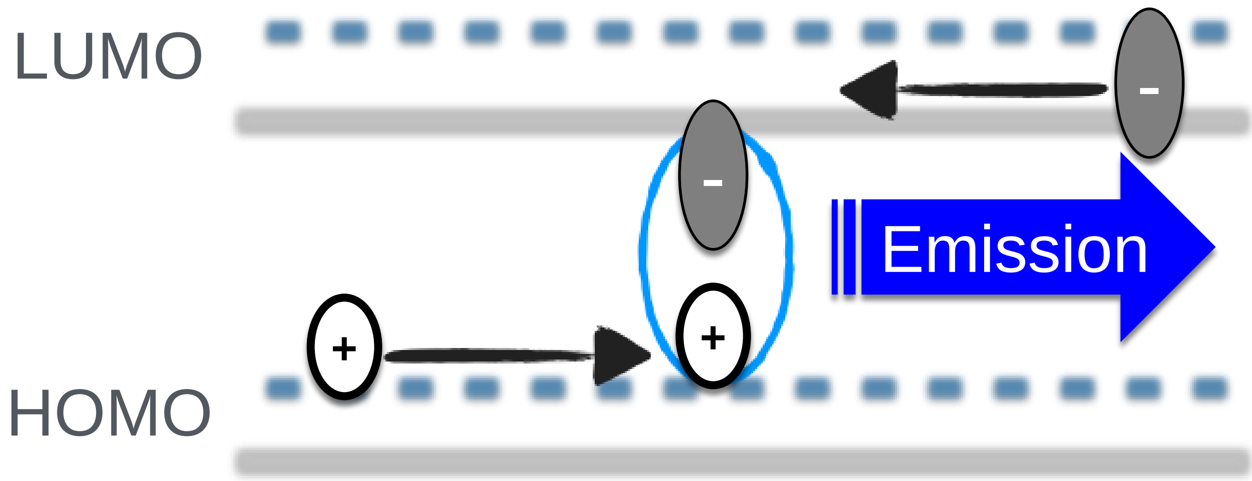
Panel 15 cm x 15 cm 82% fill factor	Single Unit WOLED*	2 Unit WSOLED
Luminance [cd/m²]	**3,000**	**3,000**
Efficacy [lm/W]	**49**	**48**
CRI	**83**	**86**
Luminous Emittance [lm/m²]	7,740	7,740
Voltage [V]	4.3	7.4
1931 CIE	(0.471, 0.413)	(0.454, 0.426)
Duv	0.000	0.006
CCT [K]	2,580	2,908
Temperature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

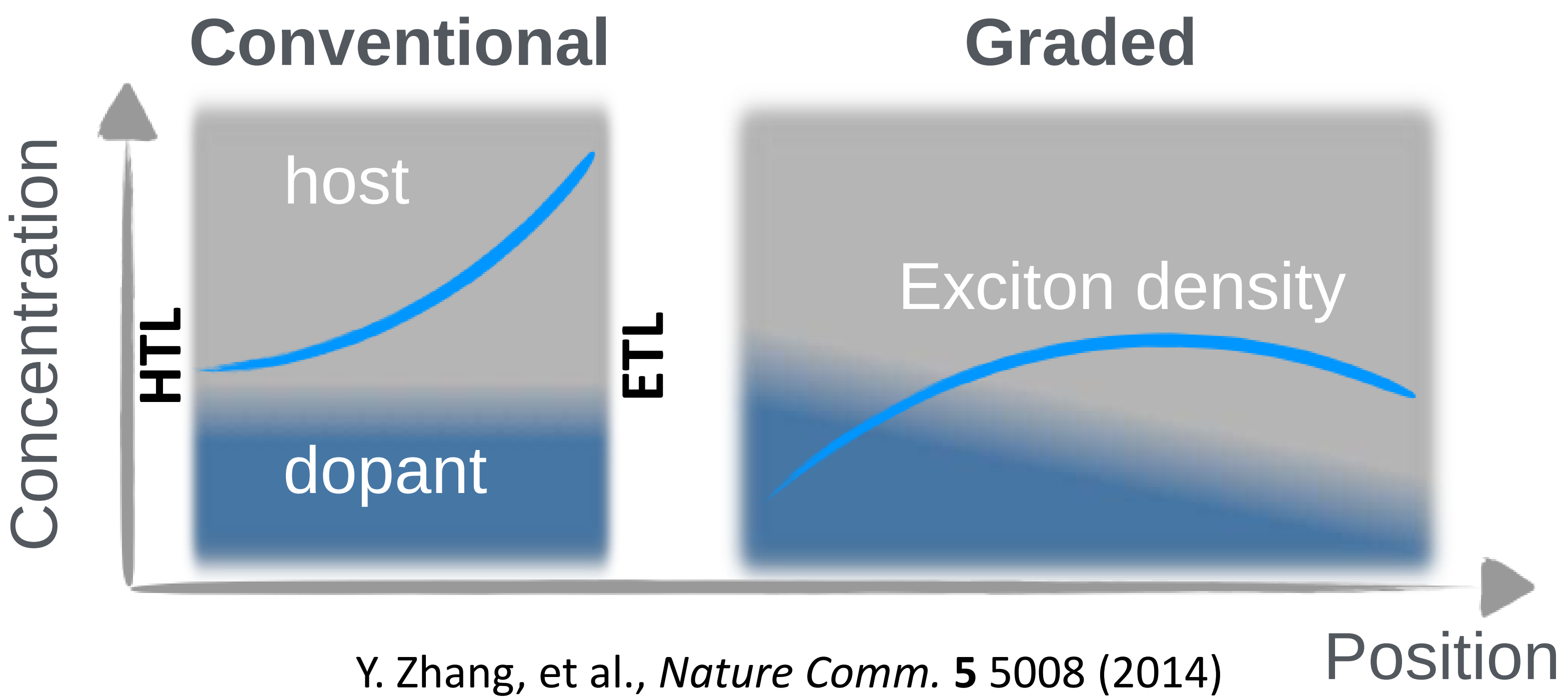
SOLED : ~ 3x LT_{70} improvement vs. single unit WOLED with similar color and power efficacy



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

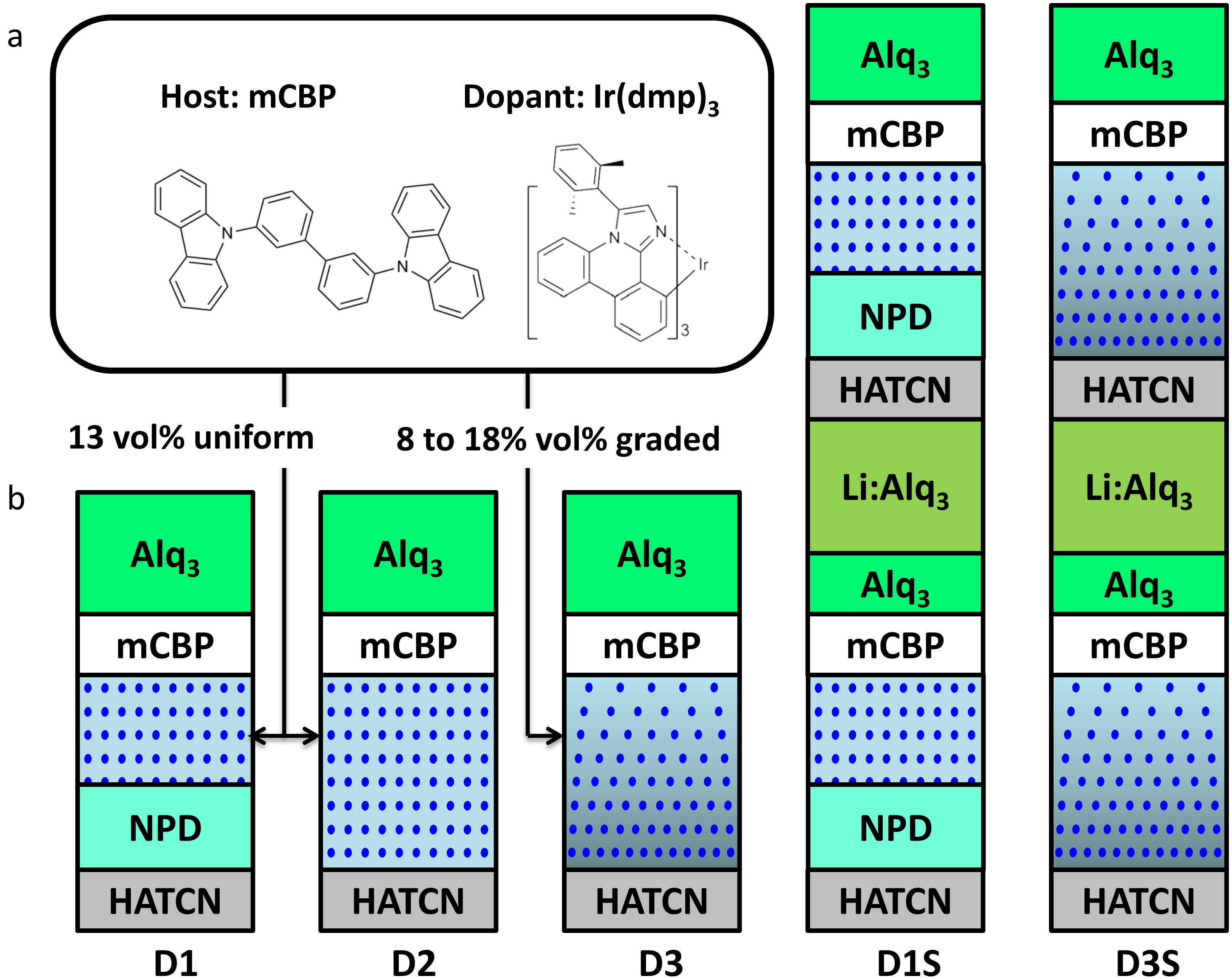
Reducing Exciton Density to Increase Lifetime



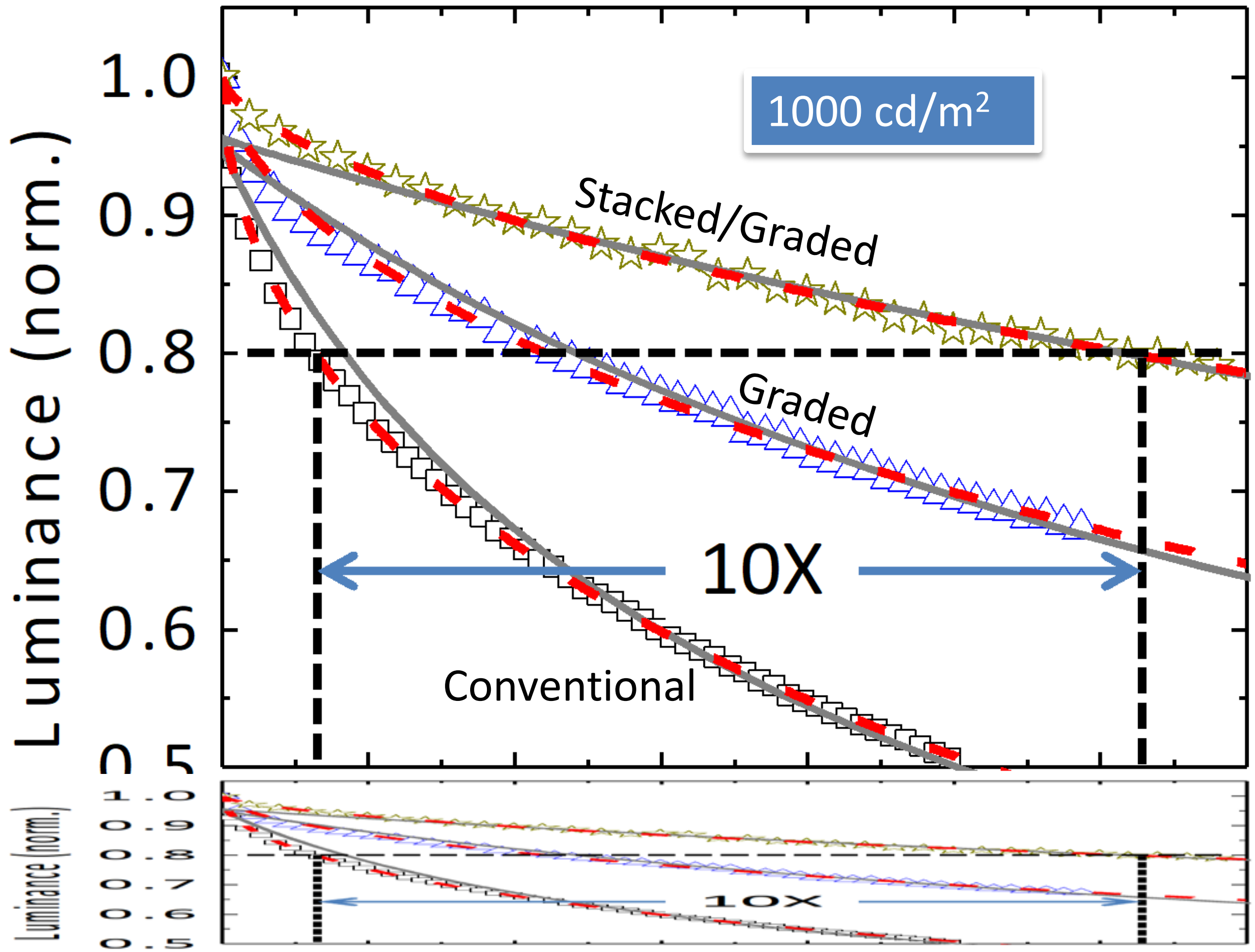


Y. Zhang, et al., *Nature Comm.* **5** 5008 (2014)

Spreading the recombination zone: Dopant/Host Grading



10 X Blue PHOLED Lifetime Improvement

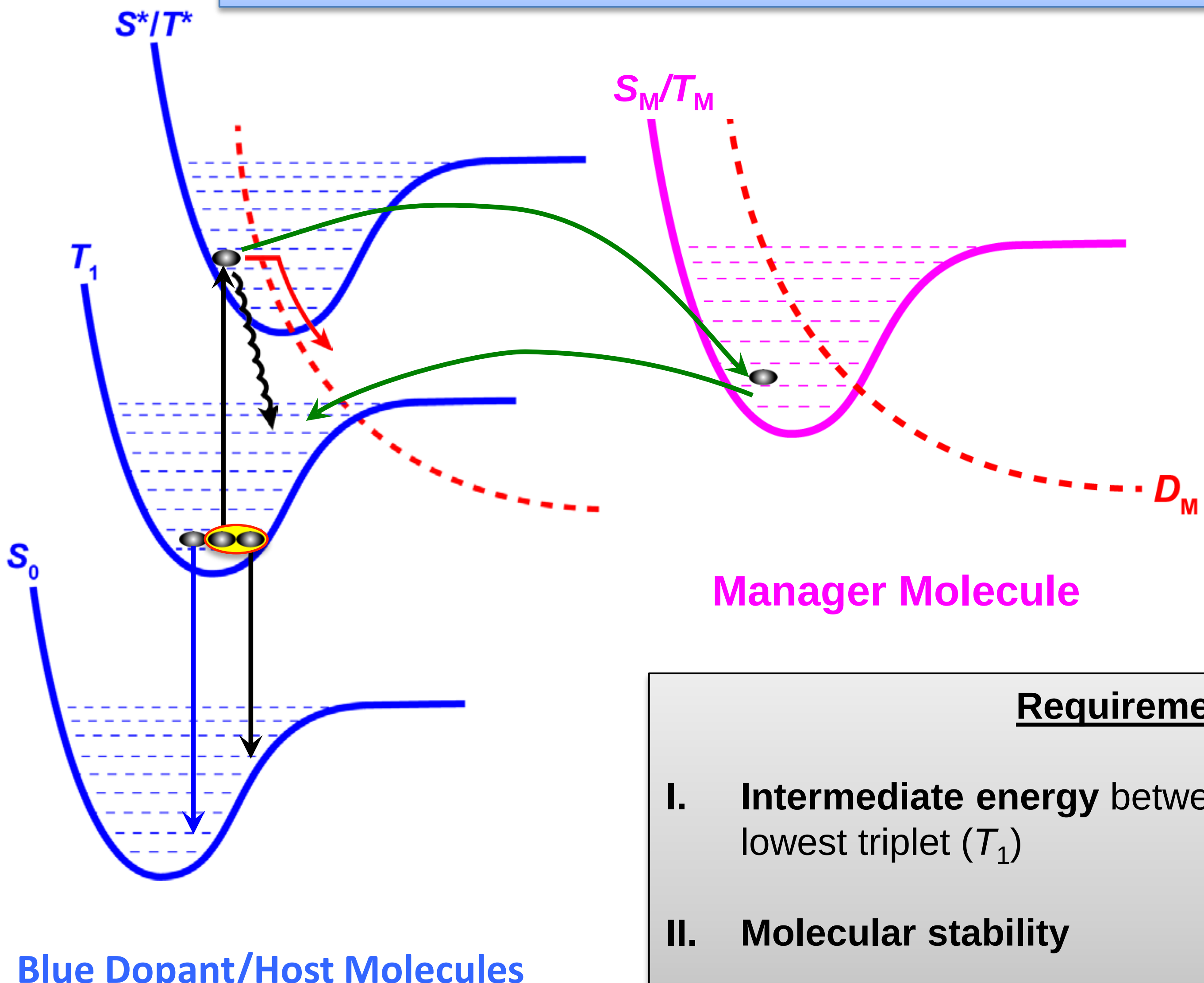


Y. Zhang, et al., *Nature Comm.* **5**, 5008 (2014)

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)

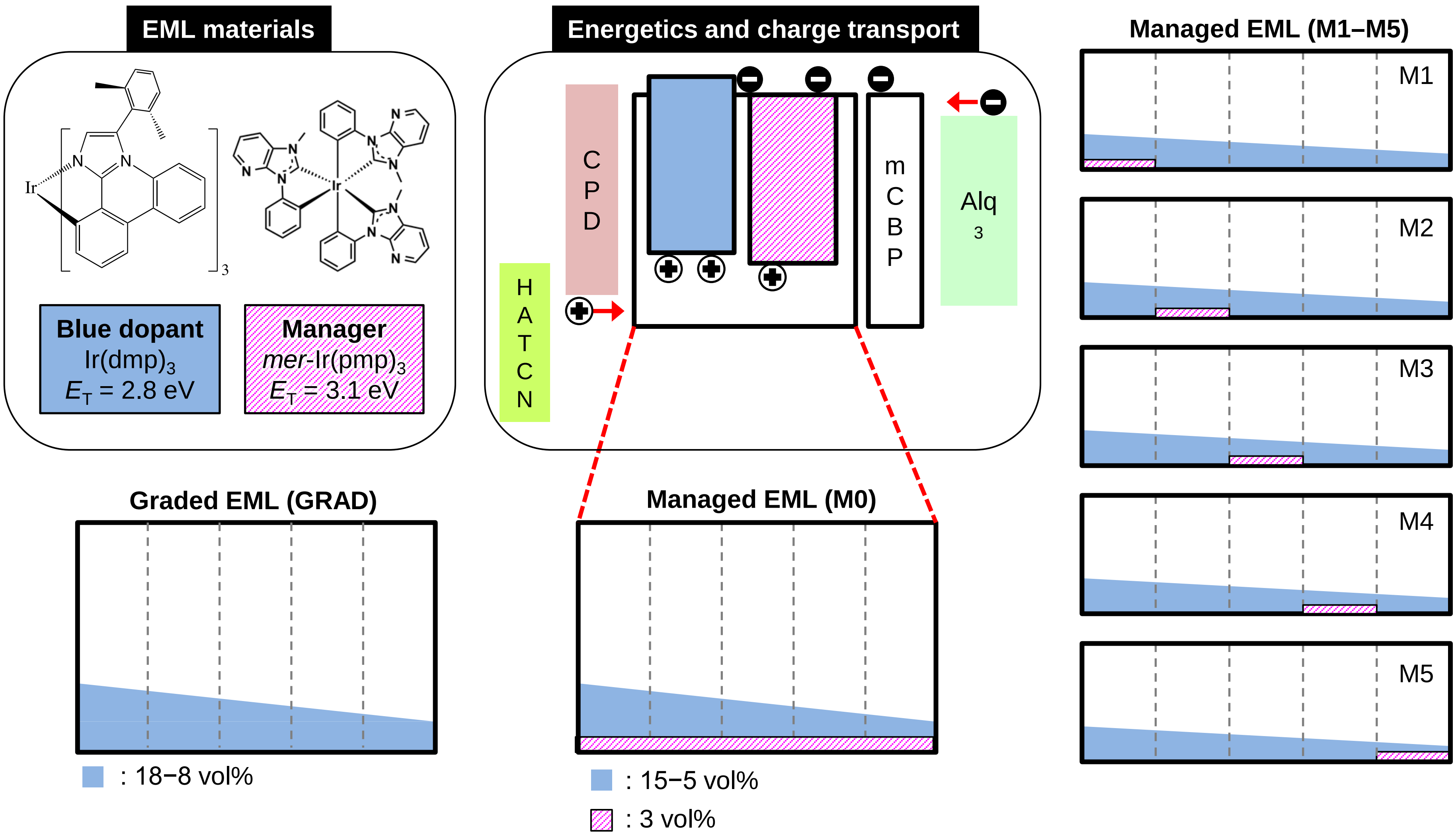
Requirements

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

II. **Molecular stability**

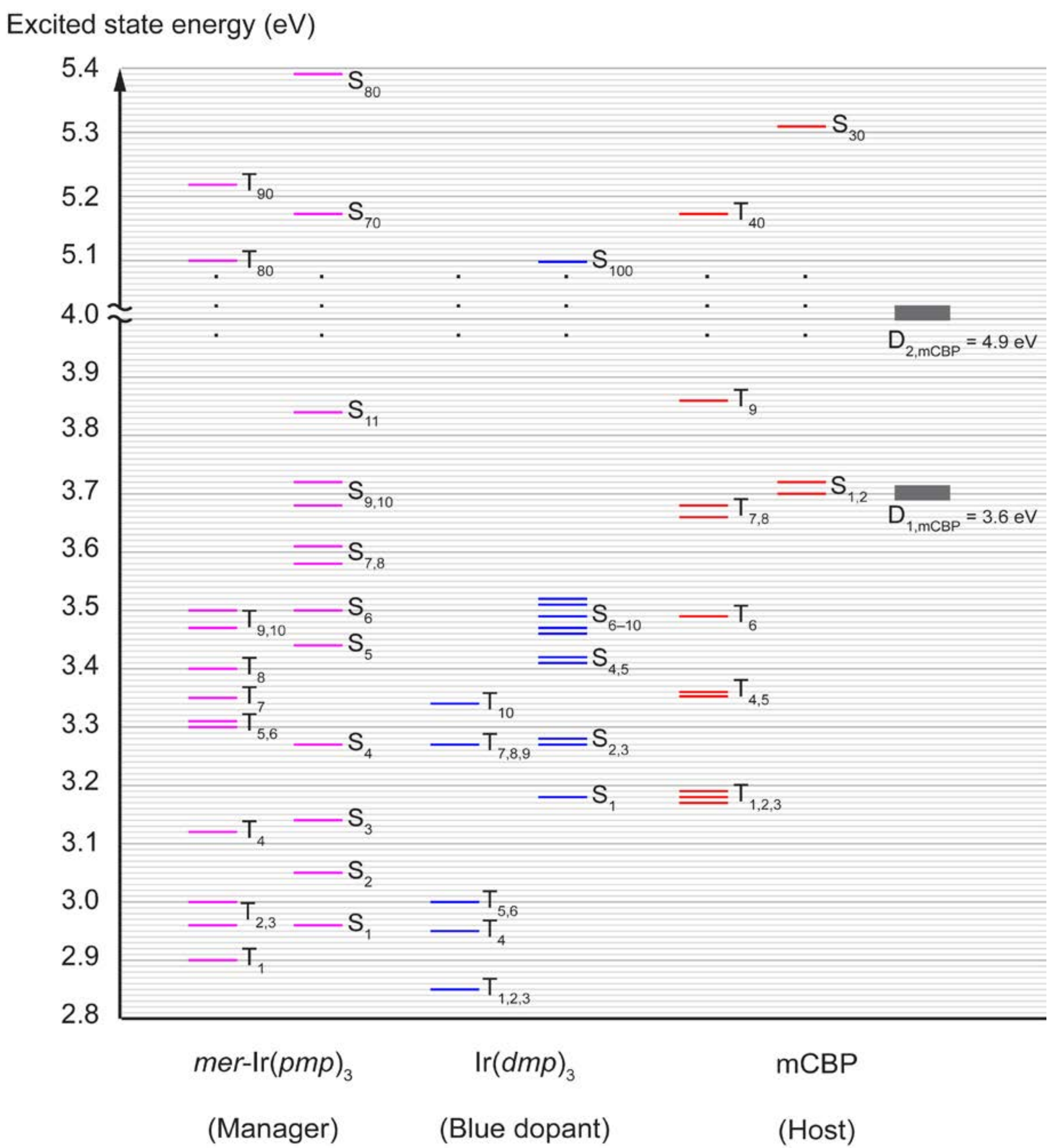
III. **Fast energy transfer** from dopant/host to manager

Managed blue PHOLEDs

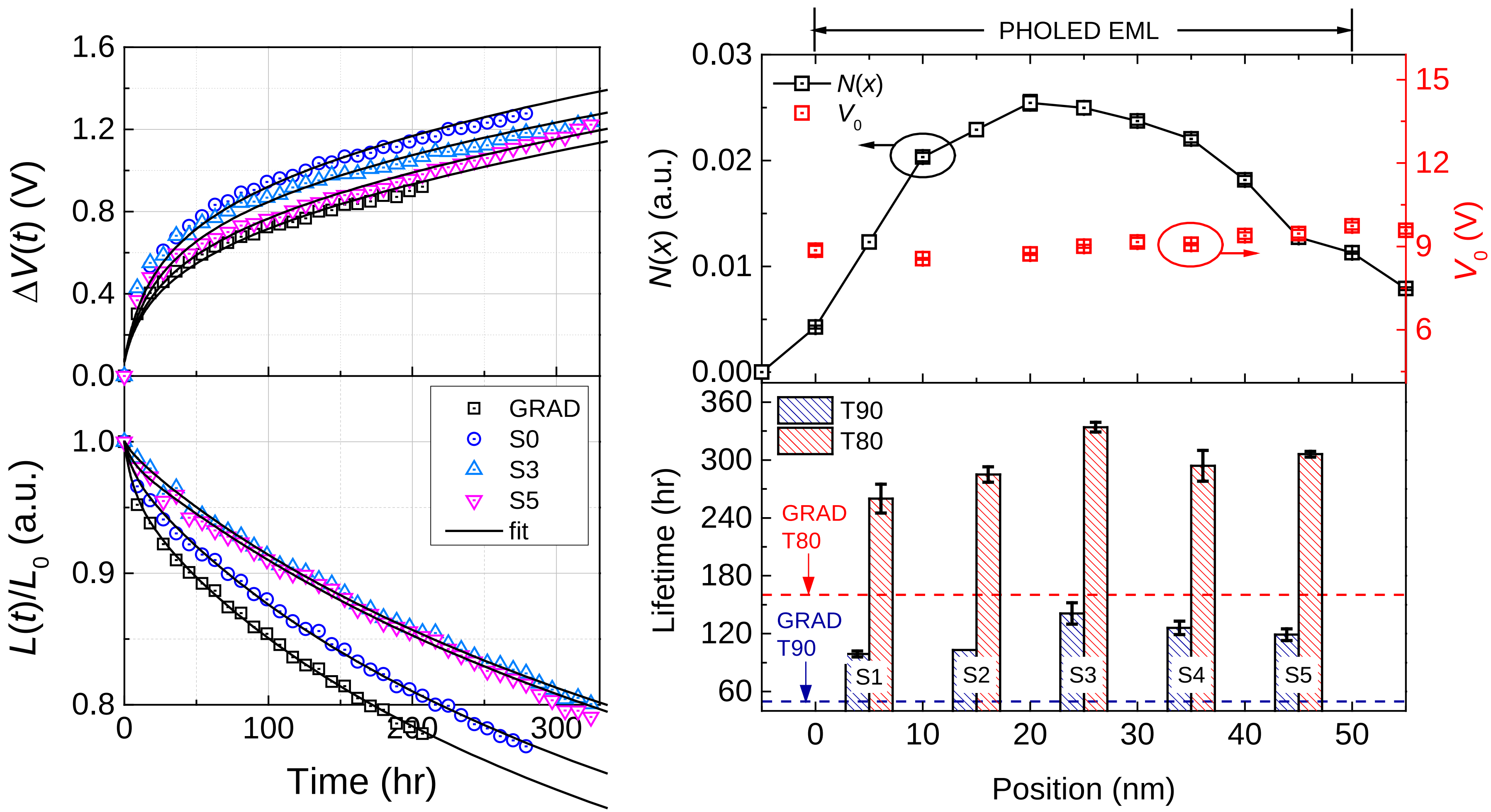


J. Lee, et al. Nat. Comm. (2017)

Plenty of Energy Levels to Resonate



Lifetime Improvements and TTA Model



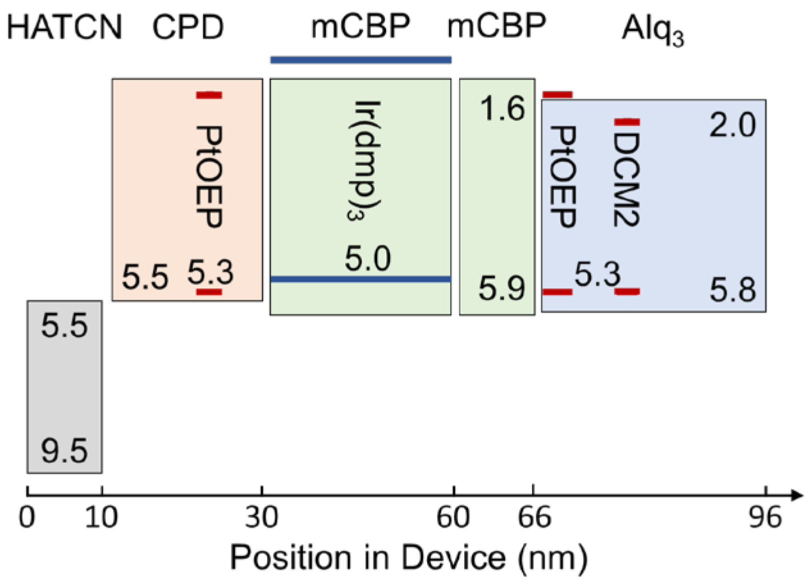
- Greatest improvement in lifetime when manager at position of highest exciton density (S3)
- Fractional increase in lifetime decreases with time
  - ➢ Greater at T90 than T80 ➔manager depletion

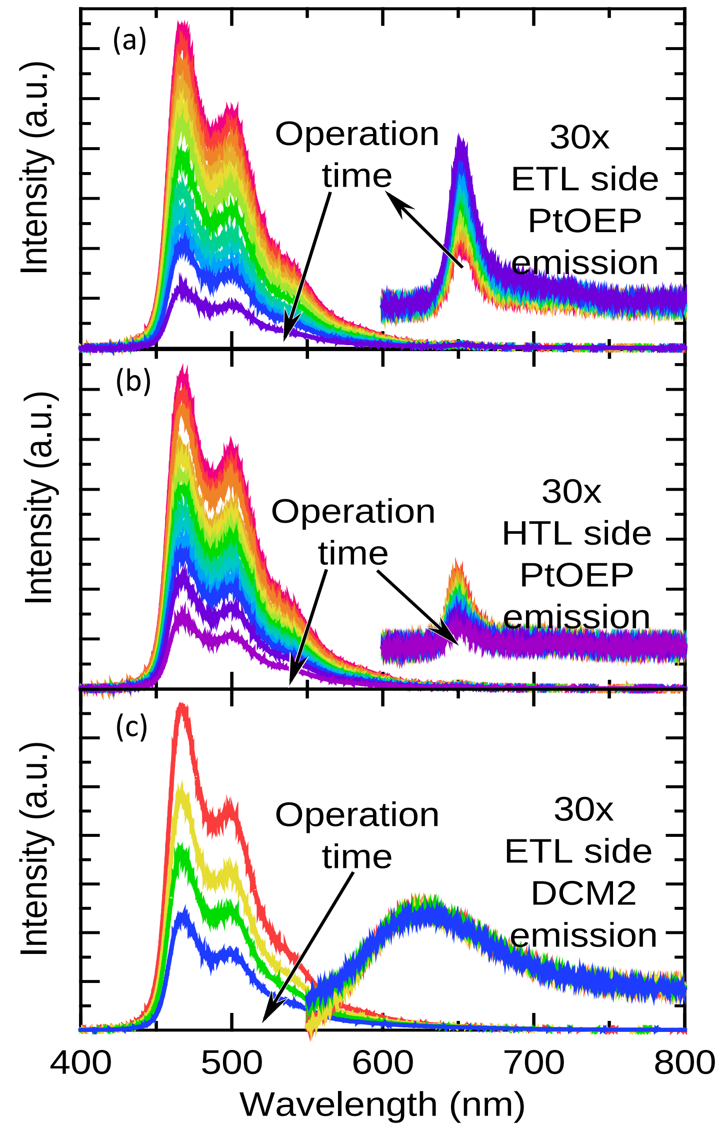
Performance Summary

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. in press (2017)

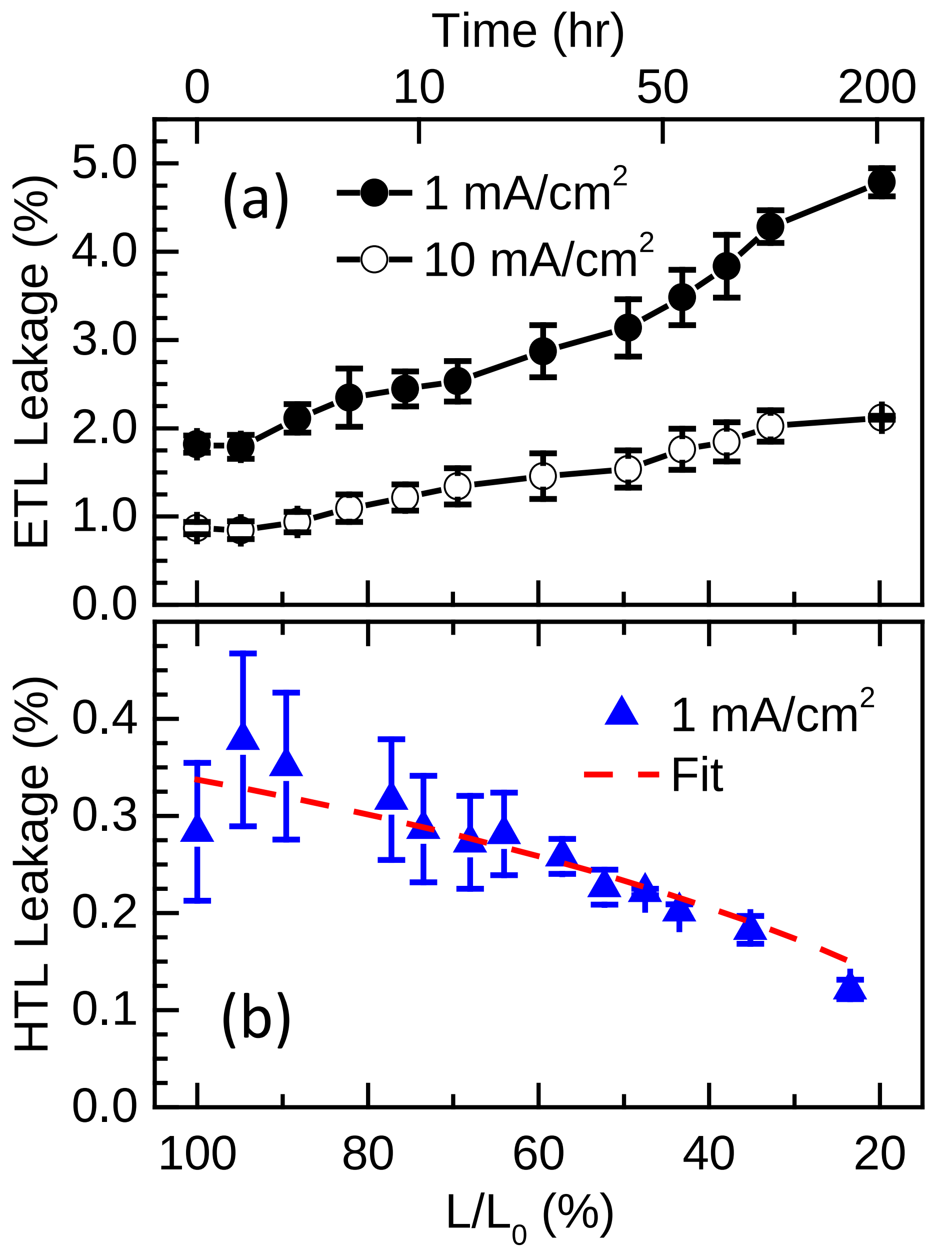
Does Leakage into Adjacent Layers Contribute to Luminance Loss?



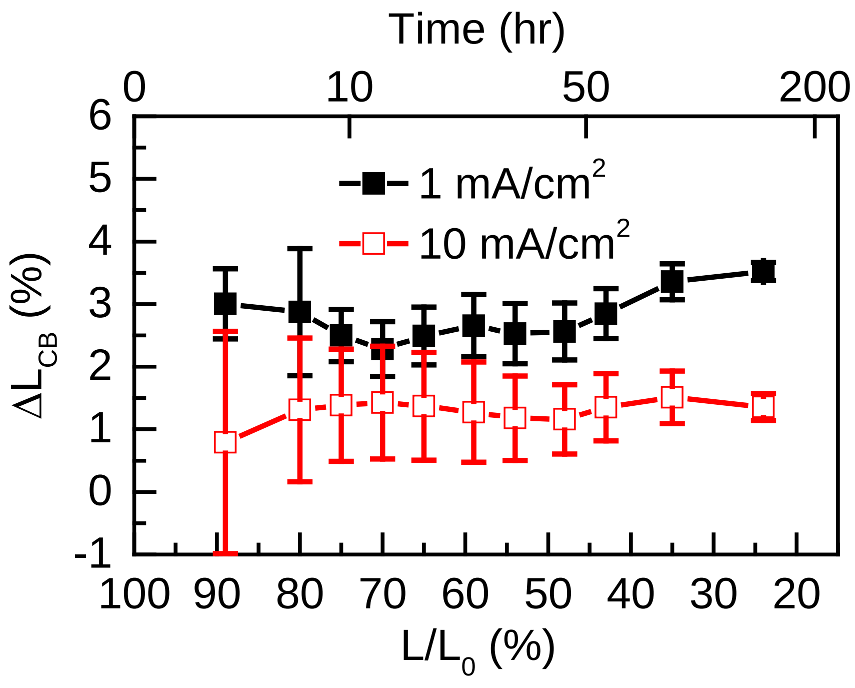


- Insert fl and ph sensor layers in adjacent layers
- Monitor change in sensor luminescence with time
- Determine contribution to total luminance change

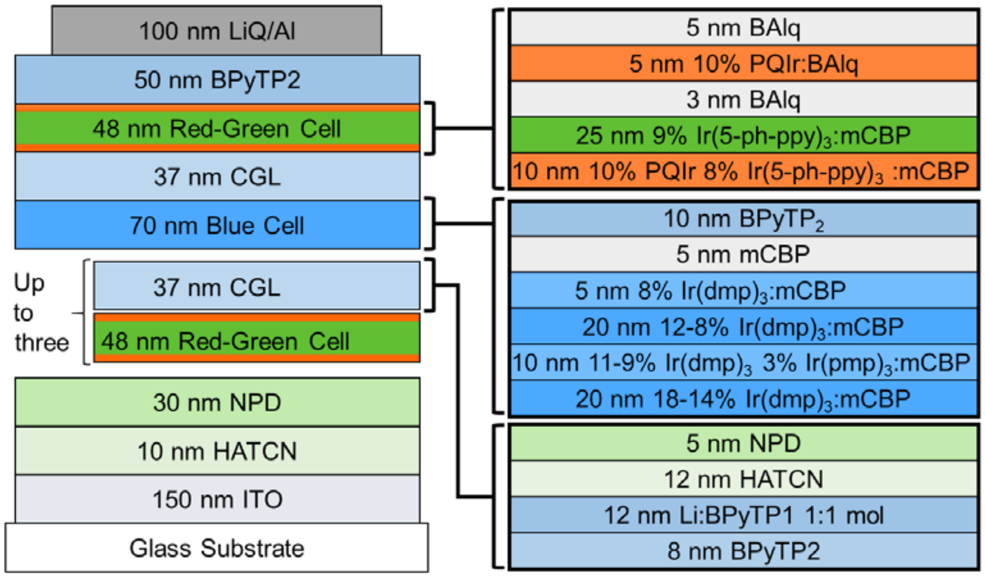
Separate measurements of ETL and HTL Leakage



Answer: Leakage Results in only Marginal Change in L



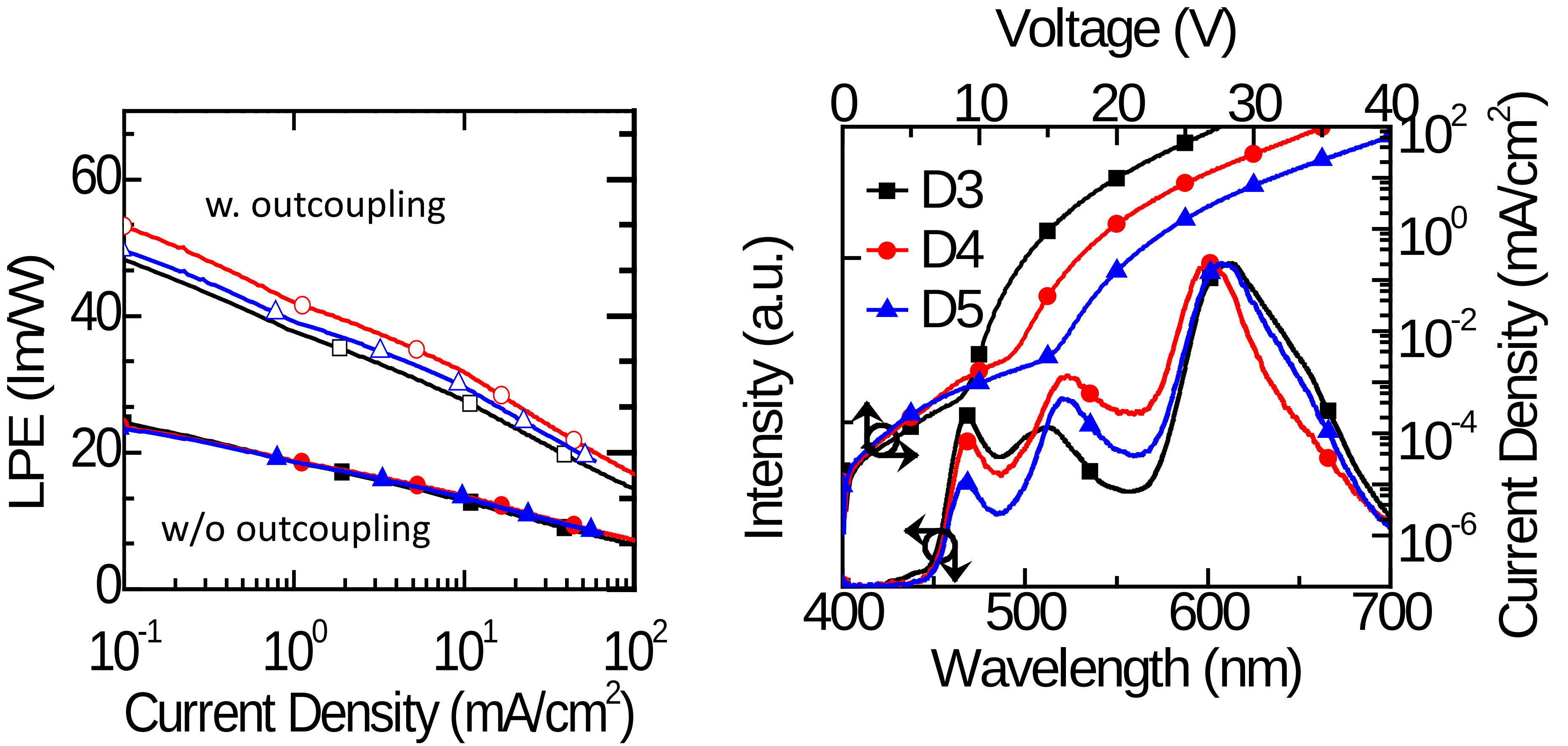
Putting Management to Work:
Long lived all phosphor stacked WOLEDs



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

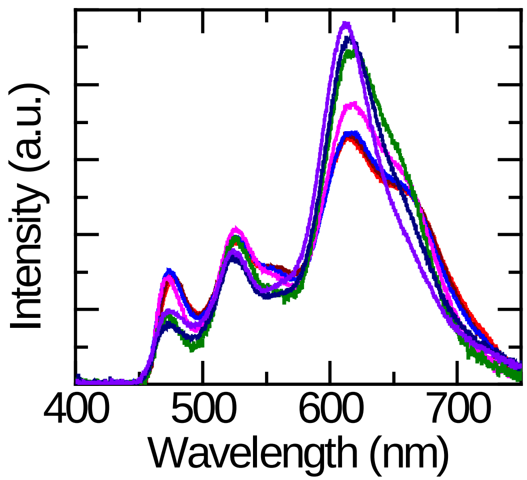
Photo illustrating good color rendering of the SWOLEDs in this report. The luminaire comprises 36 pixels (2 mm^2) operated at 50-100k nits

All Phosphor WOLED Performance

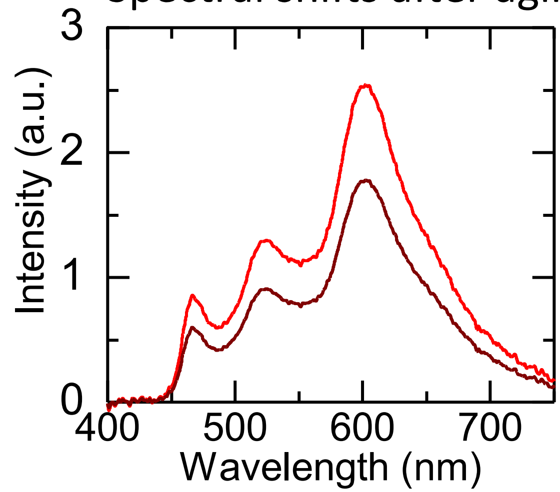


All Phosphor SWOLED Performance

0-60 Degree Angular Spectrum

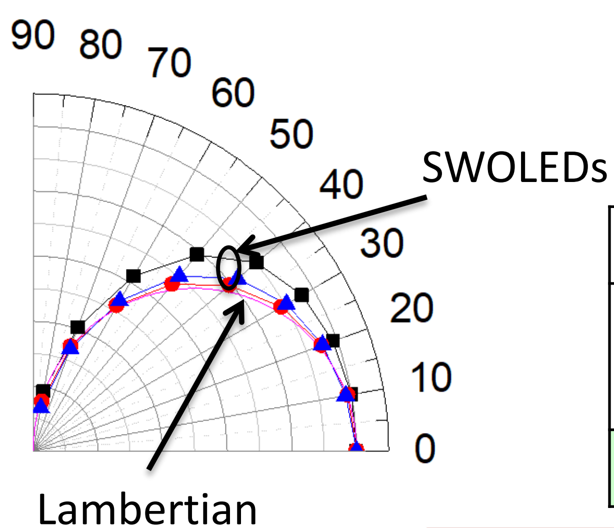


Spectral shifts after aging



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

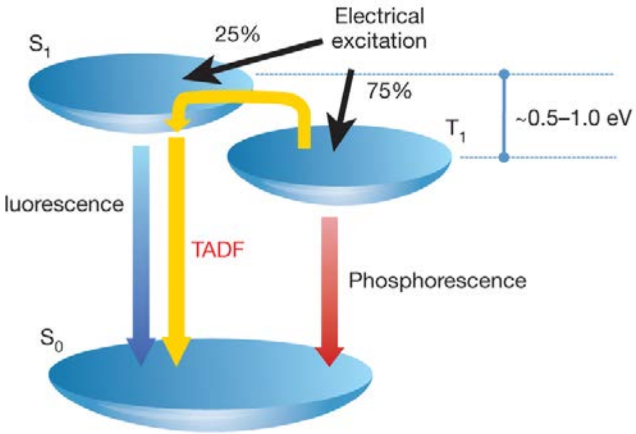
SWOLED Architecture	**Blue degradation @ WOLED T70:**
Conv	T28
Grad-Managed	T48



	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%

Lifetime primarily limited by R/G sections

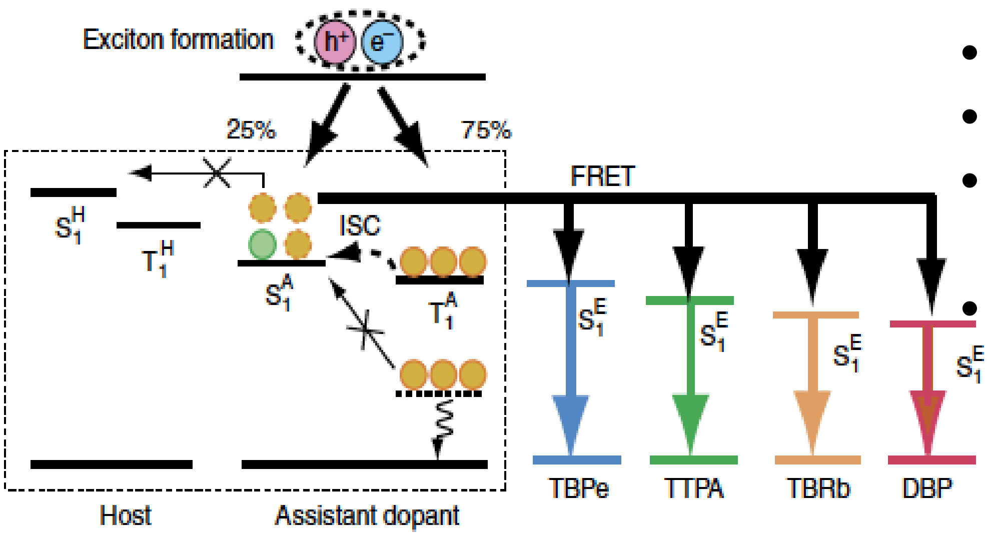
What about TADF?



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

- 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

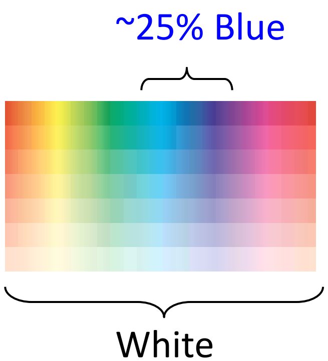
TADF sensitized fluorescence

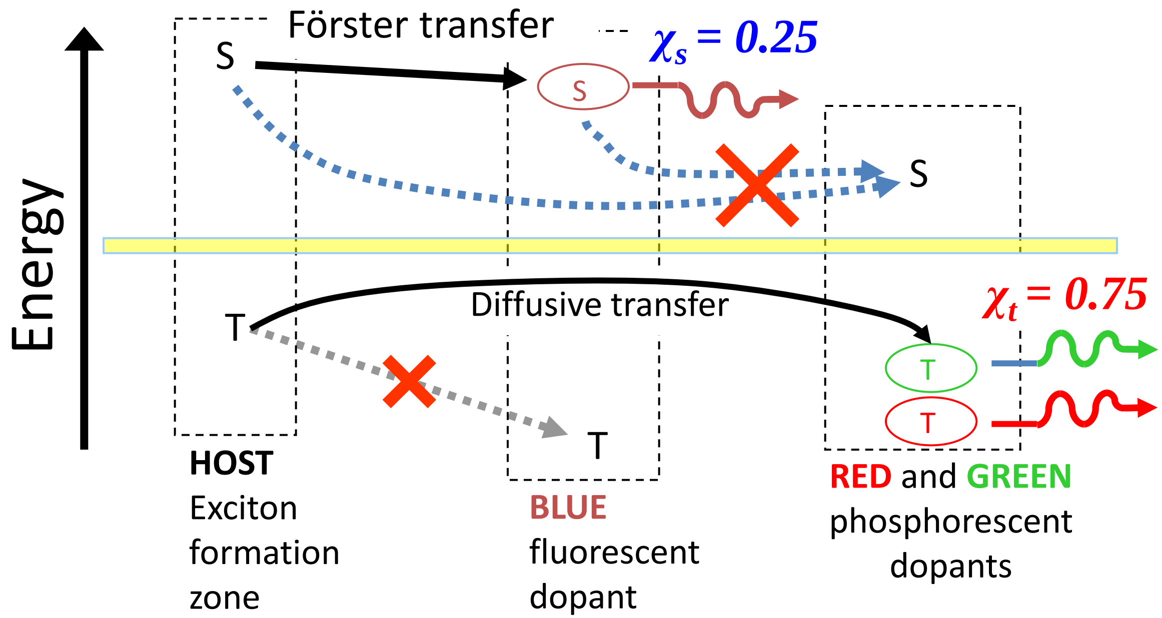


Nakanotani, Adachi, et al., Nature Comms. 2014

- Similar concept to phosphor sensitized fluorescence (Baldo, et al., 2000)
- Narrow spectra
- Long lived triplets: 1-20μs
- Excitations maintained in triplet manifold
- Need UV sensitizer to access blue fluorescence dopant energies
  - ➢ **Degradation too rapid to be practical** for lighting applications

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

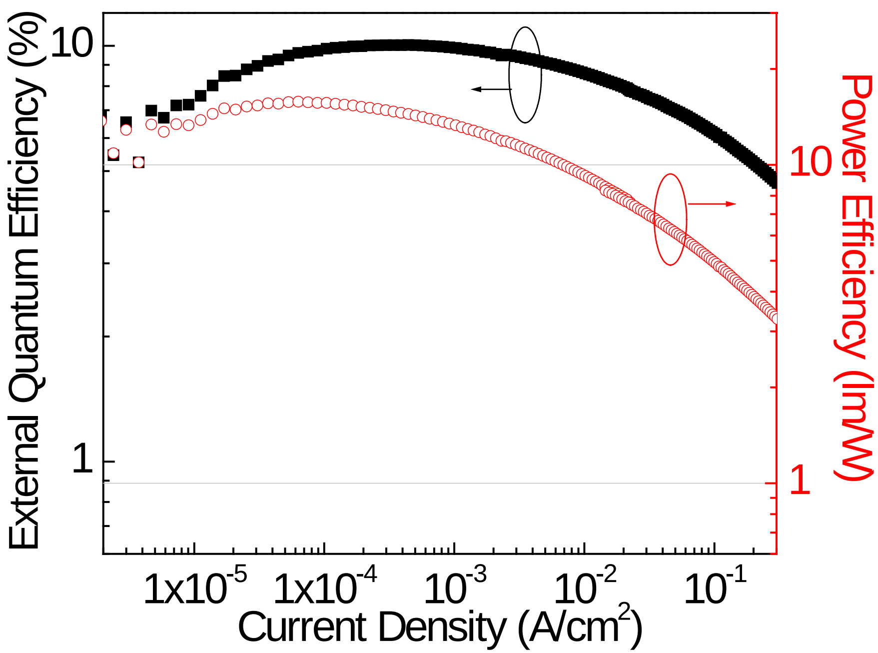
(Y. Sun, et al., *Nature*, **440**, 908, 2006)

Performance of WOLED

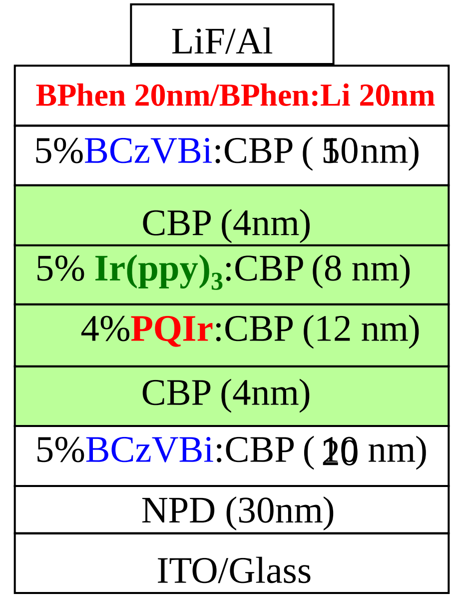
(Y. Sun, et al., *Nature*, **440**, 908, 2006)

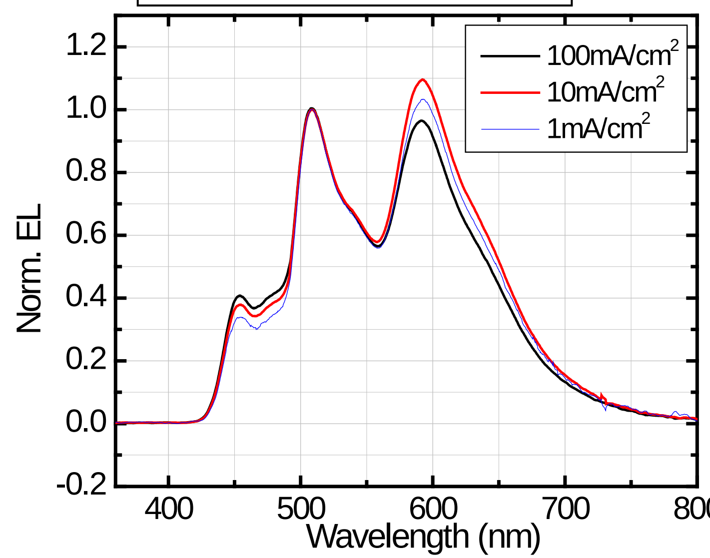
Forward viewing:

- Quantum Efficiency (10.0±0.2)%
- Power Efficiency (15.8±0.3) lm/W
- Color Rendering Index (CRI): **84** at 1, 10 mA/cm², 83 at 100 mA/cm²
- CIE: (0.40, 0.44) → (0.39, 0.43)



(see poster by Mark Thompson)





Where do we go from here?

- Find better managers
- Lower the frontier orbitals of all constituent materials
- Understand degradation pathways of dopants and hosts
  - The EML is 97% of the problem
- Use fl/ph approaches
- **Stacked devices will always win**
- **Improve outcoupling!**
  - 70% now demonstrated (see talk by Yue Qu)
  - Can we go higher?

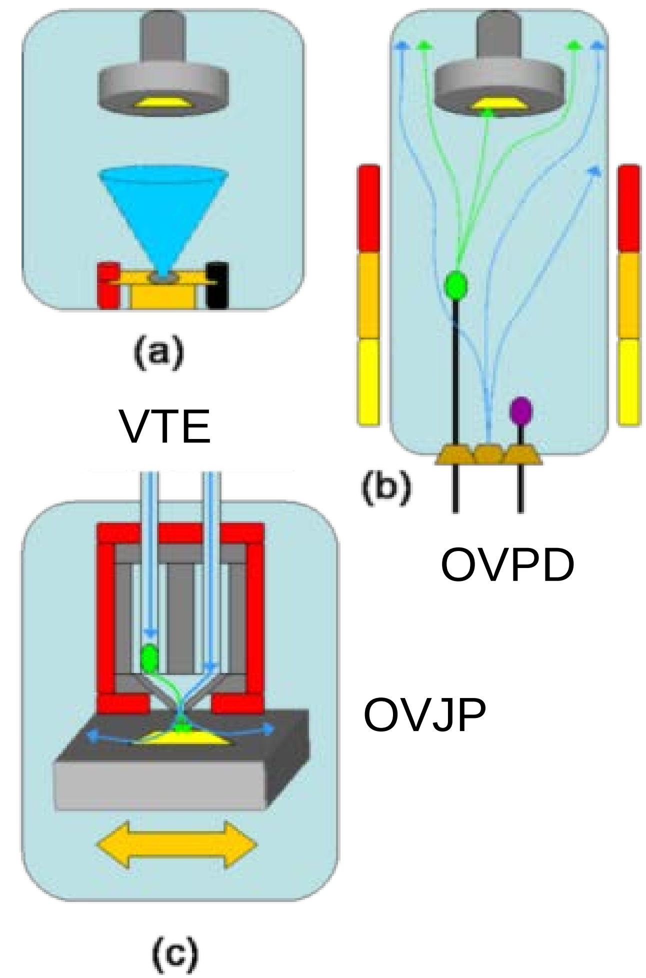
Thoughts About Patterning & Deposition

- 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….

OLED Fabrication Processes

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

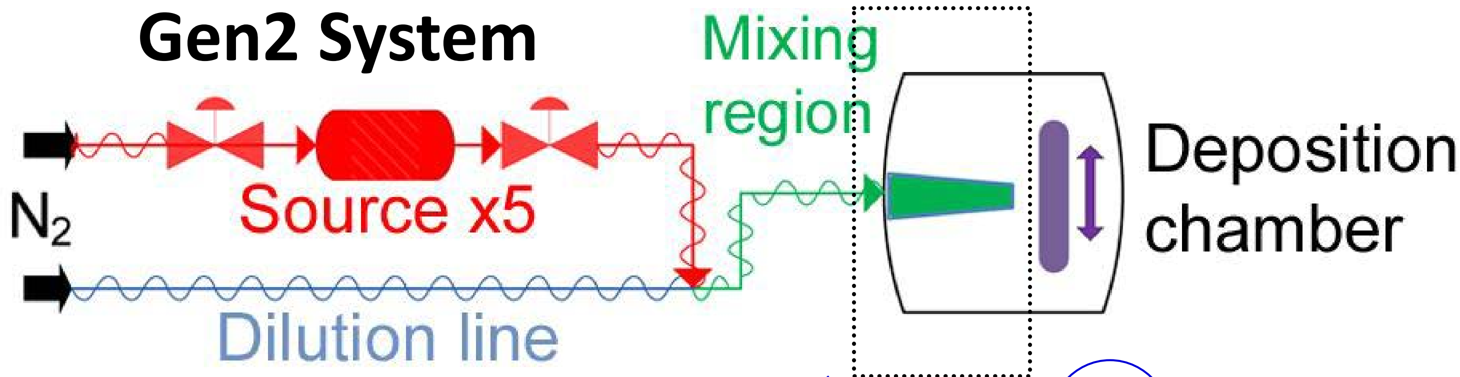
Organic PVD



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

Printing an R-G-B WOLED Using Organic Vapor Jet Deposition

Gen2 System



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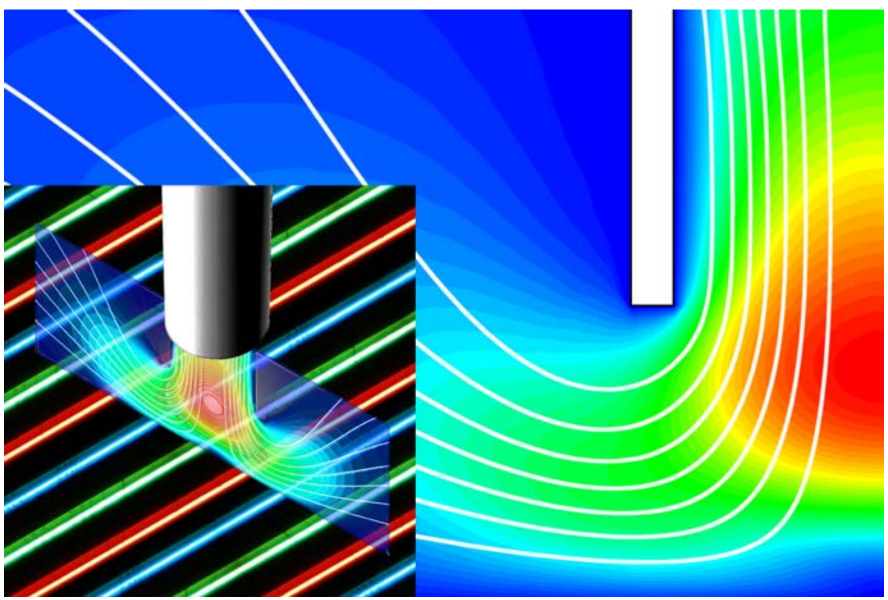
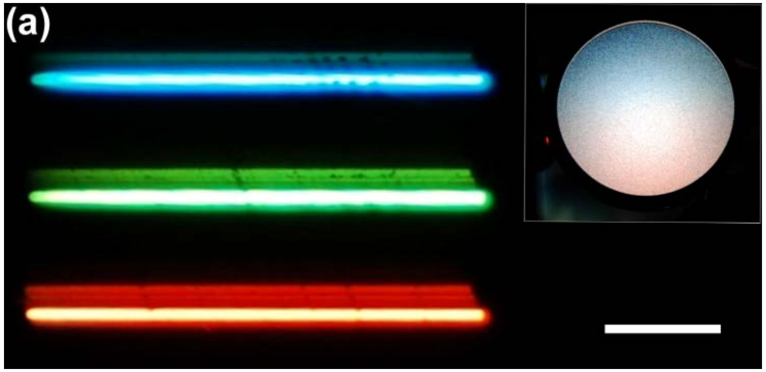
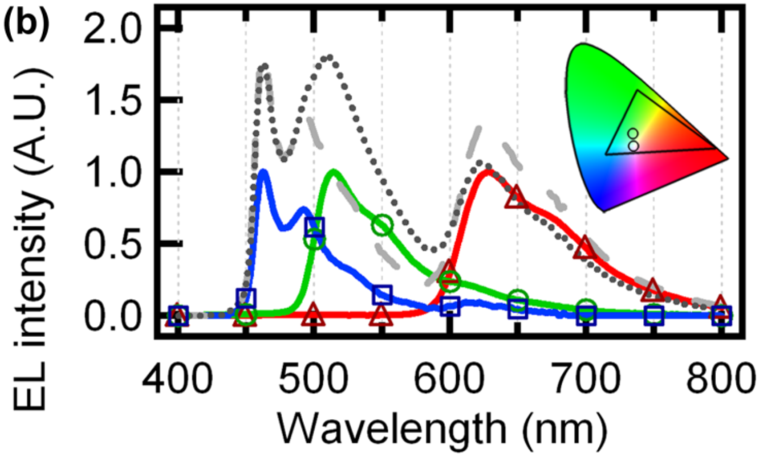


- Optimized R-G-B OLEDs can be combined to form a WOLED
- Each color separately optimized by choosing guest/host combinations
- Tunable color balance
- Motion stage beneath nozzle
- Nozzle creates high speed vapor jet

G. McGraw, et al. APL (Feb, 2008)

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