Materials and mechanisms for efficient (solid state) lighting

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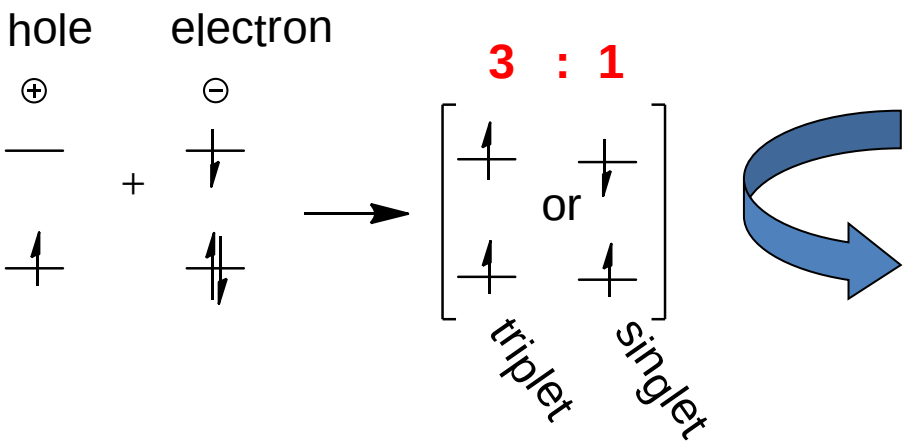
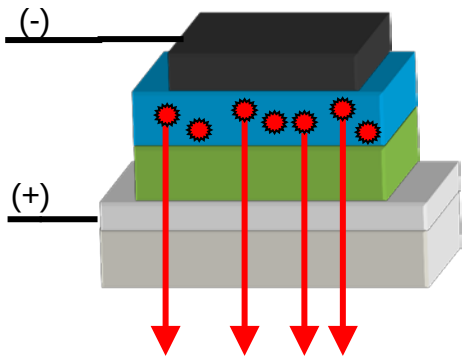
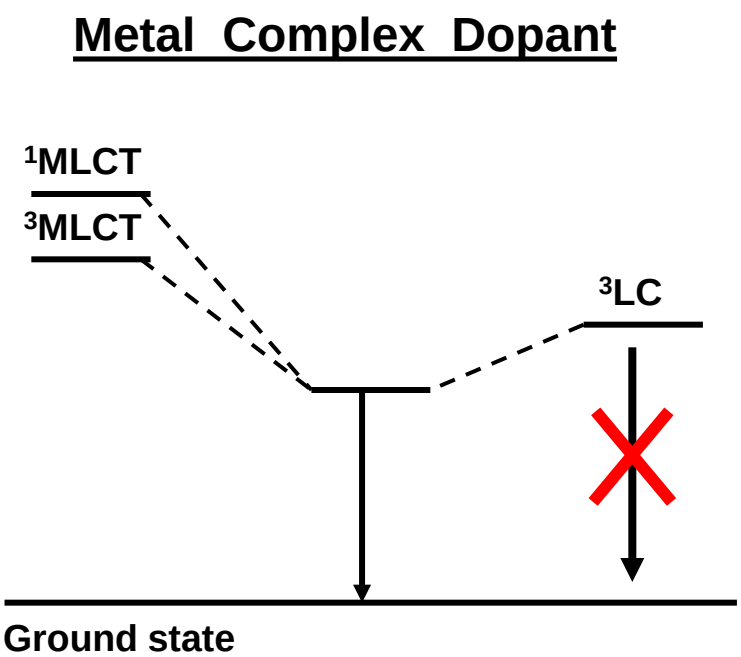
Metal facilitated triplet emission



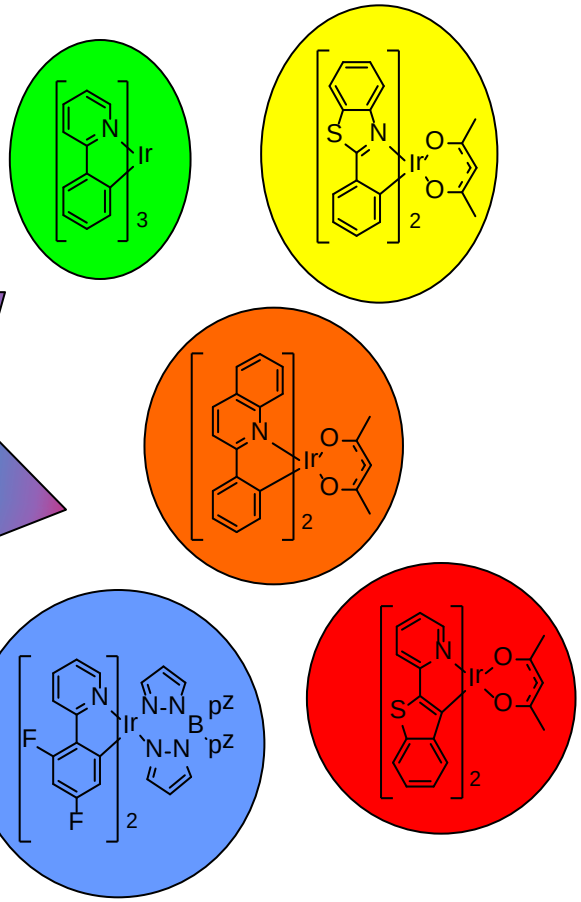


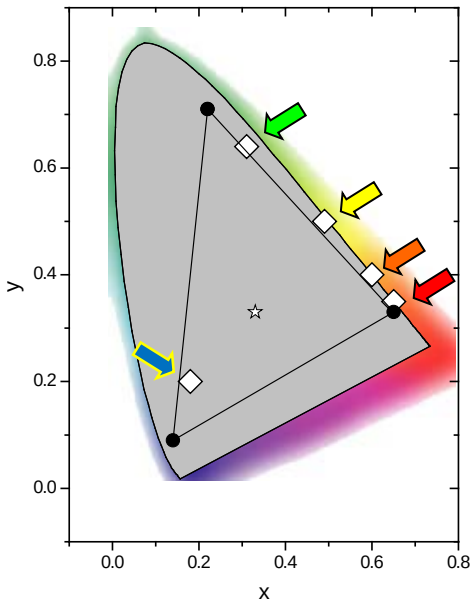


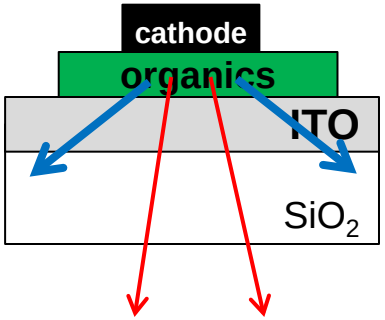
- Triplet emission is a forbidden process, luminescent lifetimes typically min. - hours
- Strong spin-orbit-coupling mixes singlet and triplet states, M = **Ir, Pt**, Os, Re, *etc.*
- Mixing of triplet states with ^{1}MLCT makes phosphorescence an allowed transition
- Can lead to lifetimes in μsec regime and high PL efficiency

Organometallic Ir complexes in OLEDs

Phosphorescence efficiency of Ir emitters are ~100%







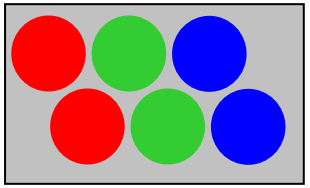
External Efficiency 15-20%

- Optimized OLEDs give external efficiency = 15-20%
  - ⇒ Internal eff = 70-100% (abs., waveguiding)
- Luminance efficiency should provide an upper limit to OLED

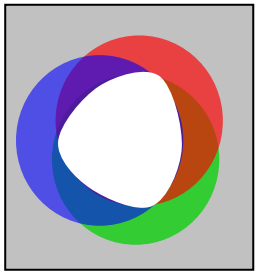
USC

Color Mixing to Achieve White Emission

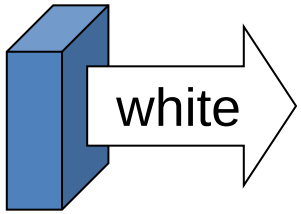
- Color mixing
- Side-by-side arrangement of RGB elements



- Transparent devices can be stacked
  - Pixels on top of pixels with a common substrate
  - Large sheets of transparent R, G and B OLEDS can be stacked to achieve white

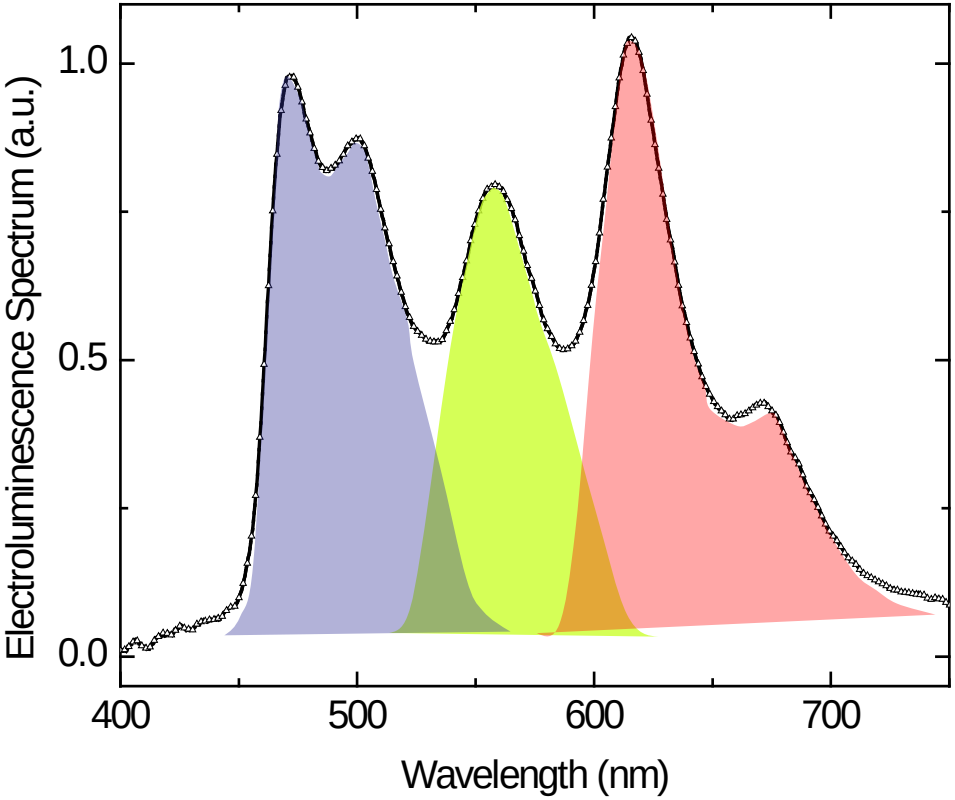


- Mixed emitters in a single device
  - Simplifies device
  - Color balance achieved automatically
  - Several possible architectures



Three phosphor white OLEDs

electrode
org
Green metal complex
Red metal complex
Blue metal complex
org
Substrate/electrode

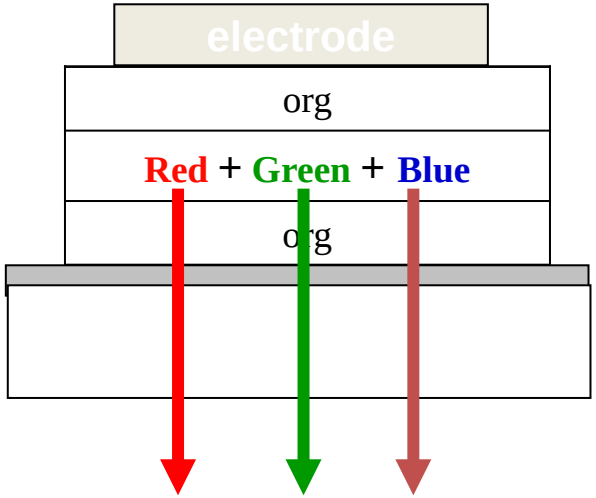


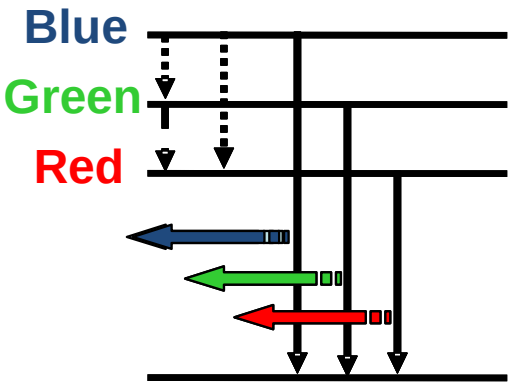
- External efficiency = 5.2%, 6 Lum/W
- Color rendering index (CRI) = 83, sunlight = 100
- Color shifts on changing intensity

D'Andrade, *et. Al.*; *Advanced Materials* (2001)

Triple Doped, Blue Energy Cascade White OLED

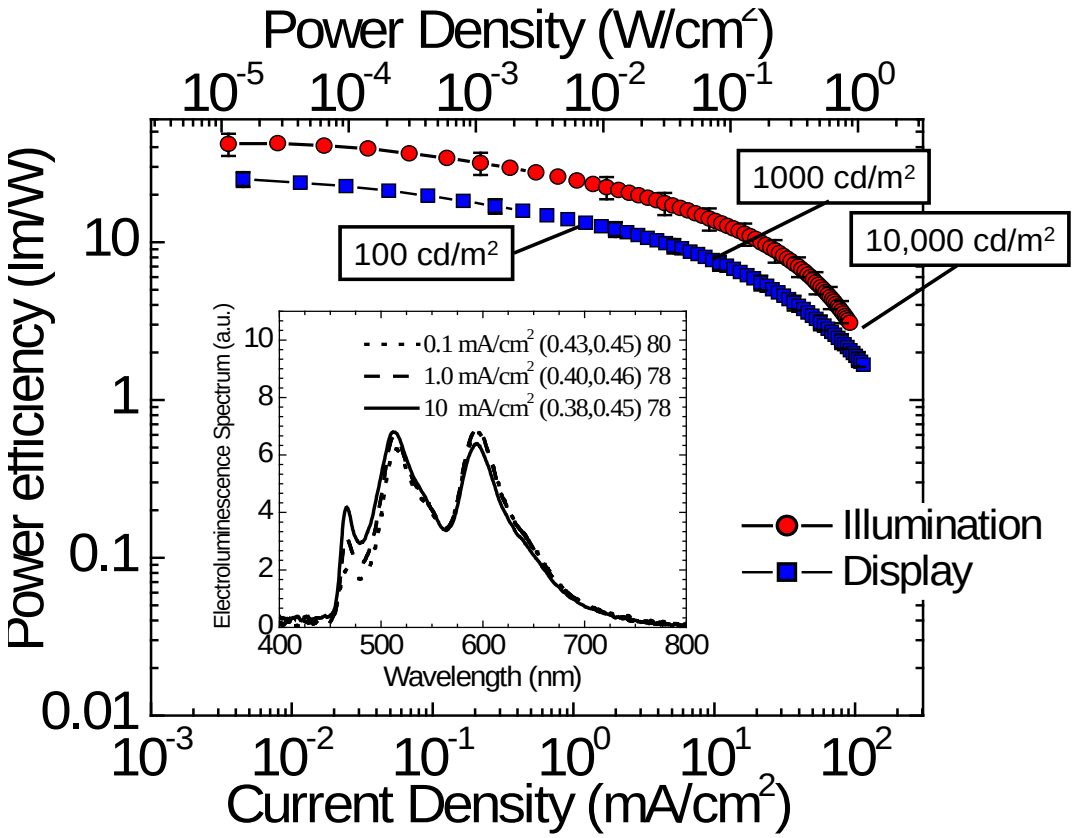
- Emission from red, green and blue in a single layer
  - Ratio of **red** : **green** : **blue** tunes color
- Device efficiency limited by blue component



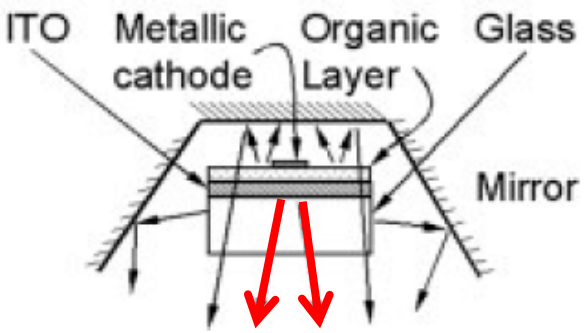


D'Andrade and Forrest, *Adv. Mat*, **2004**

Triple doped device performance



Power eff. At 1000 Cd/m²:
11 lm/W (display)
19 lm/W (illumination/total)

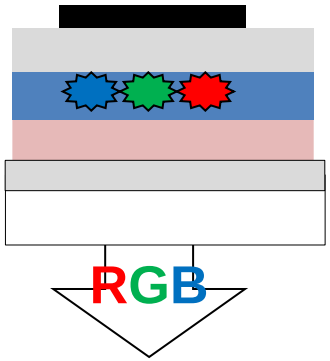


- Standard practice in lighting industry:
  - Efficient lamp fixtures are used to redirect light exiting from all surfaces into the space being illuminated

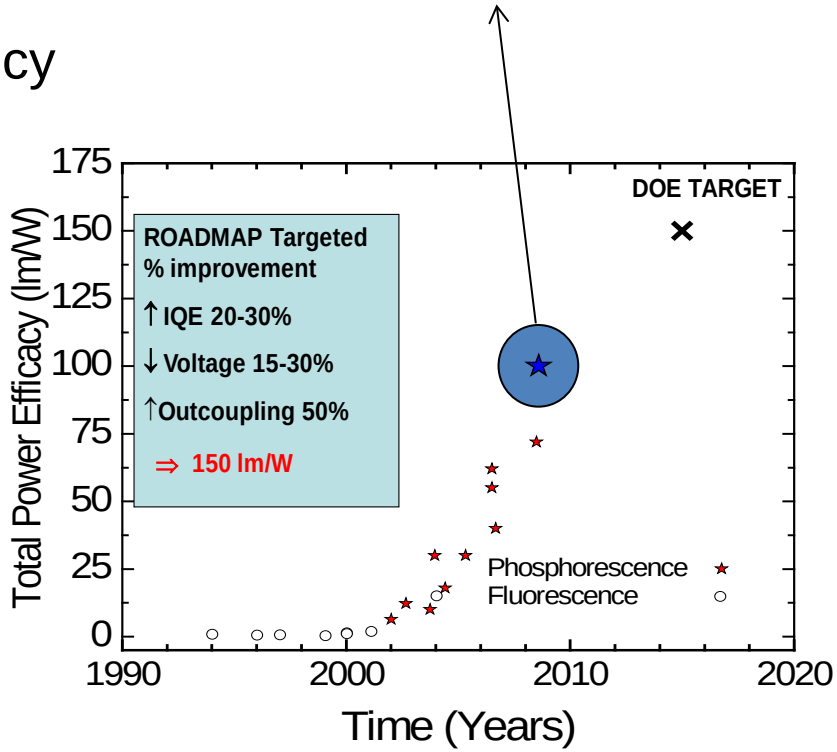
D'Andrade and Forrest, *Adv. Mat*, **2004**

White OLEDs for solid state lighting

- Multiple color centers to achieve broad band white
  - Highest efficiency is for multilayer, three phosphor white
- Challenges
  - Getting them to all emit at once
  - Achieving high efficiency for all
  - Low drive voltage at high efficiency
  - Low cost

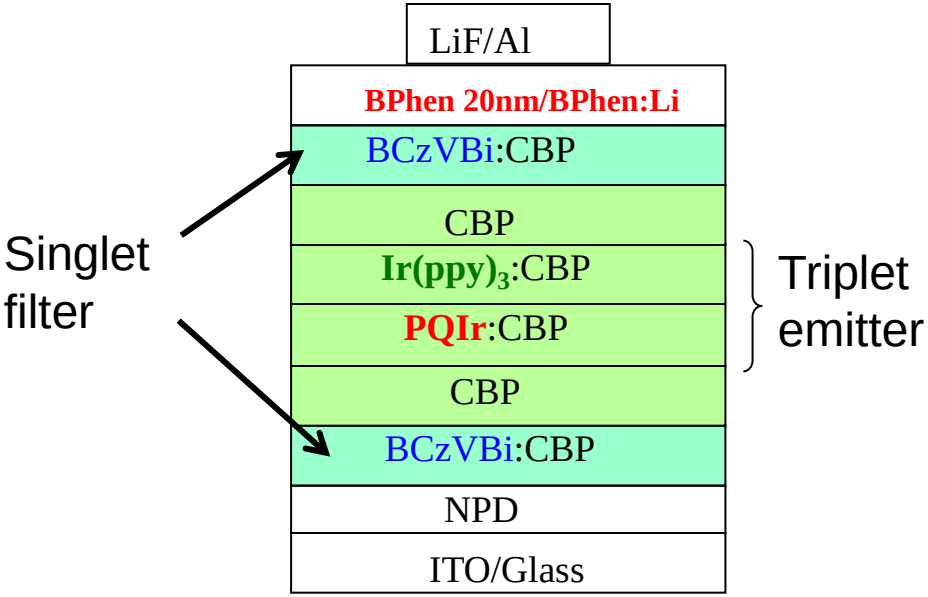


Universal Display Corp.
J. Kido, Yamagata
K. Leo, Dresden



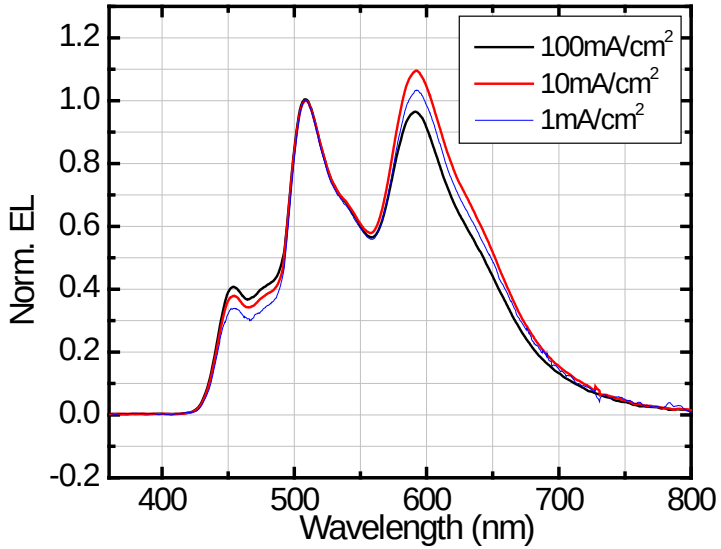
Performance of WOLED

- Display QE 10.0%
- Display Power Efficiency 15.8±0.3 lm/W
- Color Rendering Index (CRI): 83-84
- CIE: (0.40, 0.44) → (0.39, 0.43)



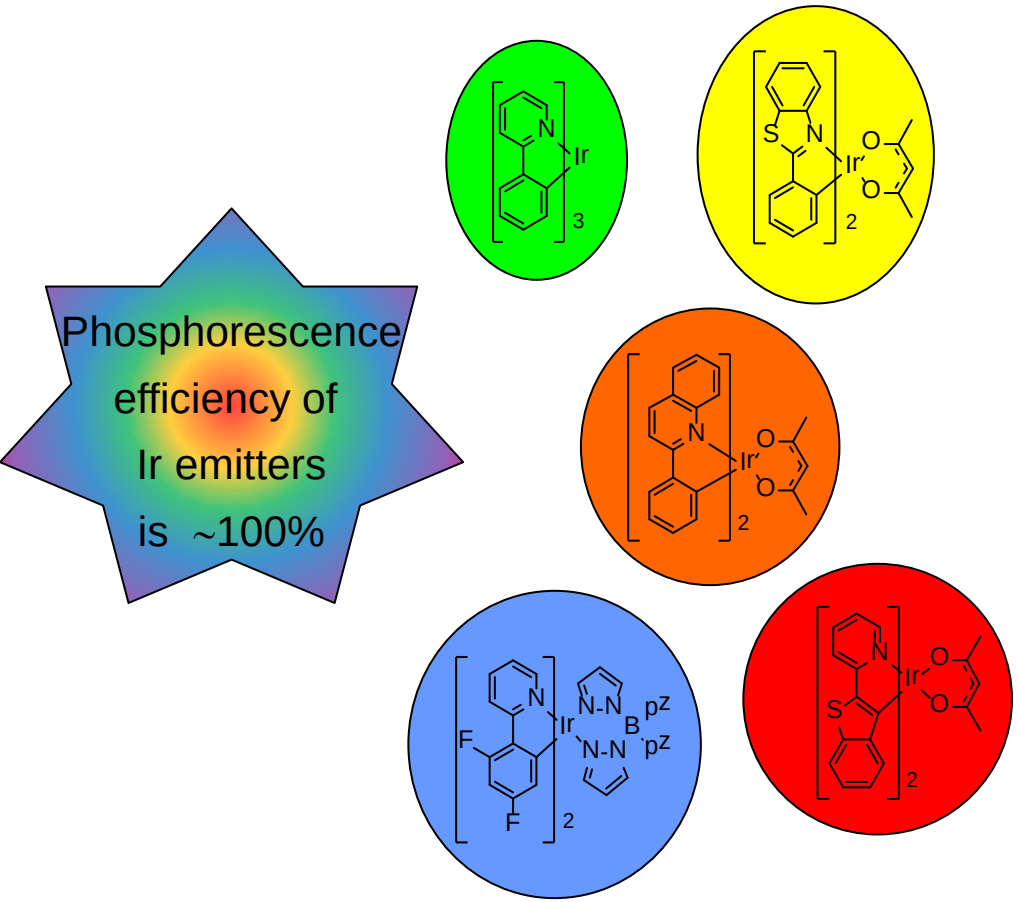
TOTAL light efficiencies at 500 cd/m^2

- Total External Quantum Efficiency:
  - ✓ (18.4 ±0.5)%
- Total Power Efficiency:
  - ✓ (23.8 ±0.5) lm/W
- K. Leo, *et. al.*, Dresden: > 45 lm/W

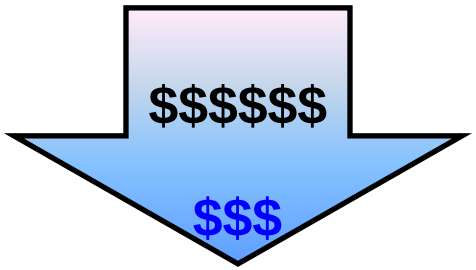


Y. Sun, *et. al.*, *Nature* (2006)

Organometallic Ir complexes in OLEDs



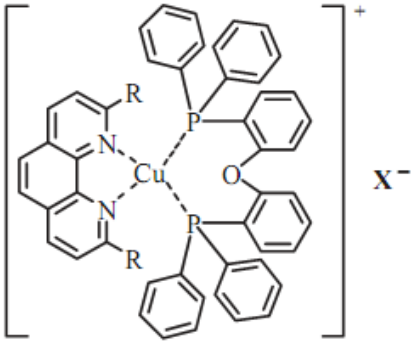
The most efficient OLEDs are based on phosphorescent iridium complex



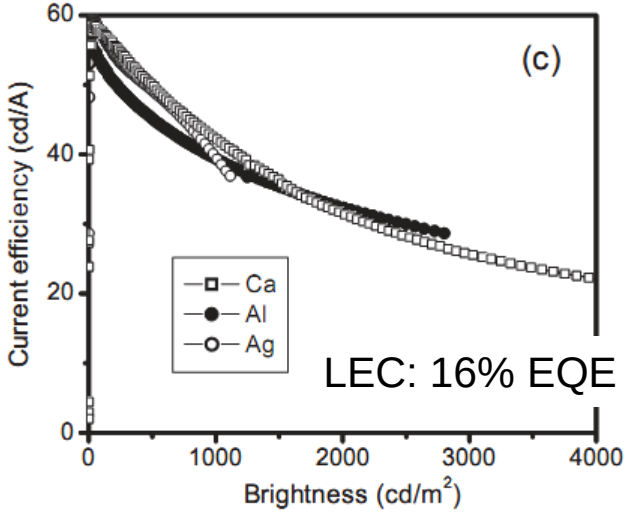
Copper complex based OLEDs

- Typical PHOLED is 6% dopant in a 30 nm emissive layer
  - 0.0018 g dopant/m^2
  - 100 g of Ir phosphor is 50,000 m^2 of lighting panel

The highest efficiency Cu based OLED/LEC

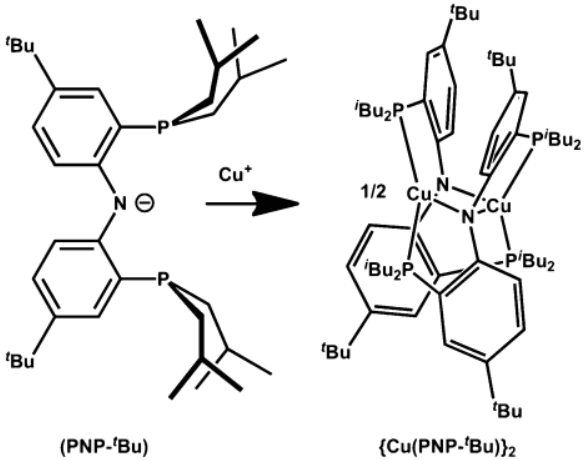


$[Cu(dnbp)(DPEphos)]^+ (BF_4^-)$, R = $(CH_2)_3CH_3$
$[Cu(dnbp)(DPEphos)]^+ (ClO_4^-)$, R = $(CH_2)_3CH_3$
$[Cu(dnbp)(DPEphos)]^+ (PF_6^-)$, R = $(CH_2)_3CH_3$
$[Cu(dnop)(DPEphos)]^+ (BF_4^-)$, R = $(CH_2)_7CH_3$

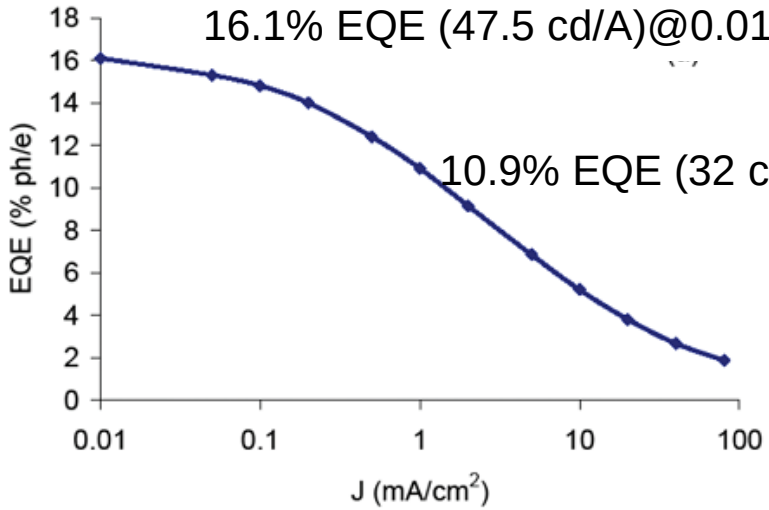


LEC: 16% EQE (56 cd/A)@4V

Adv. Mater., 2006, 16, 1203



J. Am. Chem. Soc., 2010, 132, 9499

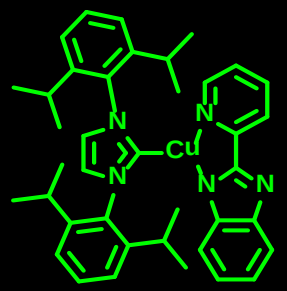


16.1% EQE (47.5 cd/A)@0.01 mA/cm^2

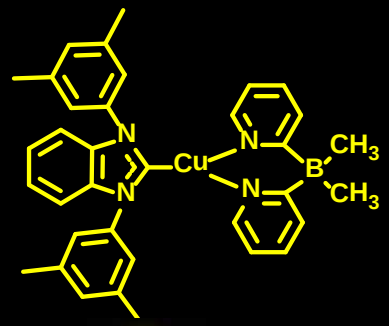
10.9% EQE (32 cd/A)@1 mA/cm^2

Air sensitive

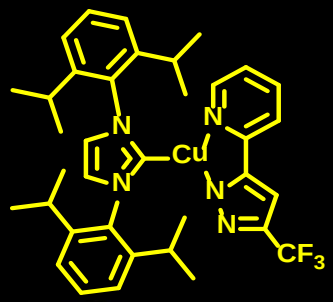
Three Coordinate Cu complexes: phosphorescent air-stable solids



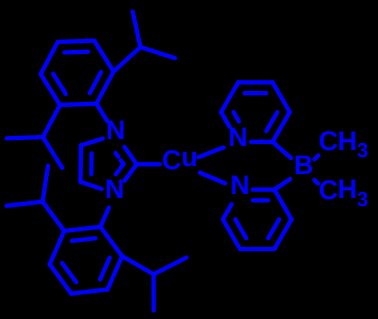
555 nm
58%
33 µs



558 nm
70%
15 µs



560 nm
62%
12 µs

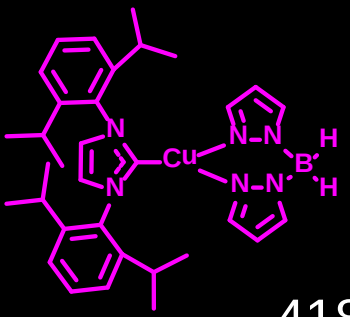


470 nm
80%
11 µs

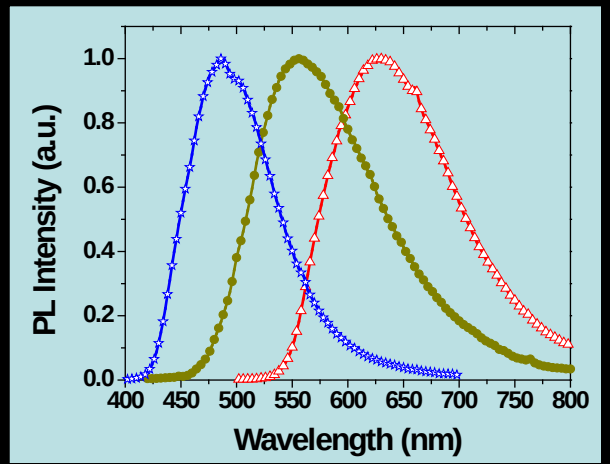
in PMMA film (2wt.%):
QY = 34%, τ = 13.8 µs

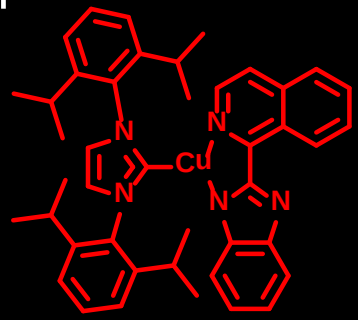
605 nm
6%
2 µs

in c-hexane:
QY = 15%, τ = 2.3 µs



418 nm
3%
16 µs





632 nm
13%

TADF-new light emitting mechanism-

$$\eta_{ext} = \eta_{\text{int}}\eta_p = \gamma\eta_r\eta_{PL}\eta_p$$

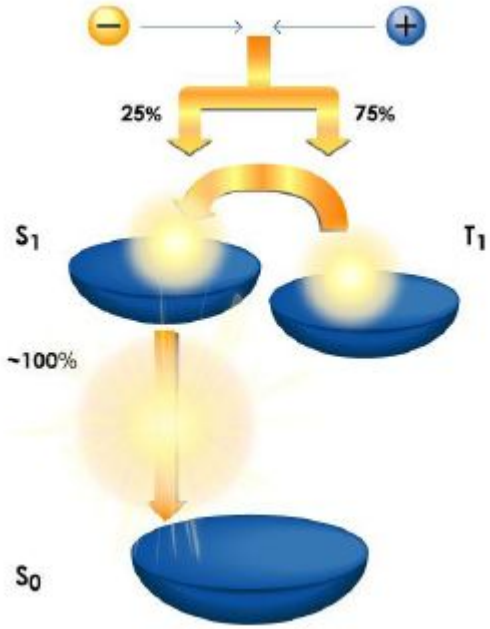
~100% 100% ~100% ~30%

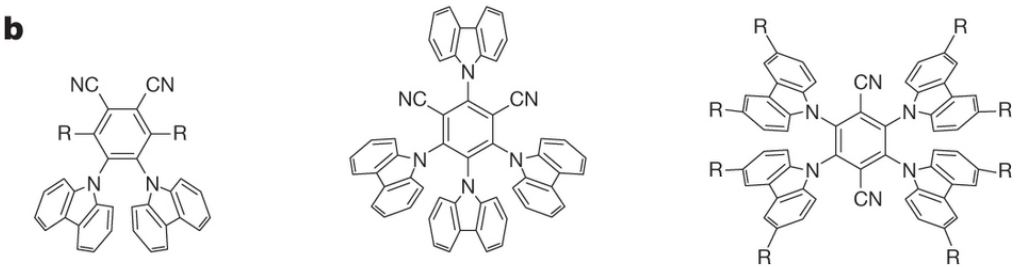
γ: e/h injection, transport and recom. eff.

η_r: emissive exciton efficiency

η_{PL}: PL quantum efficiency

η_p: light out-coupling efficiency



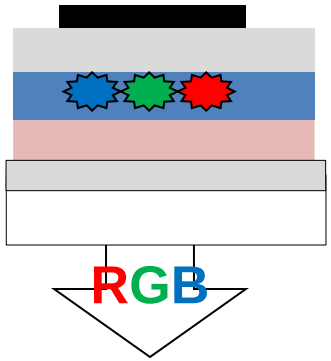
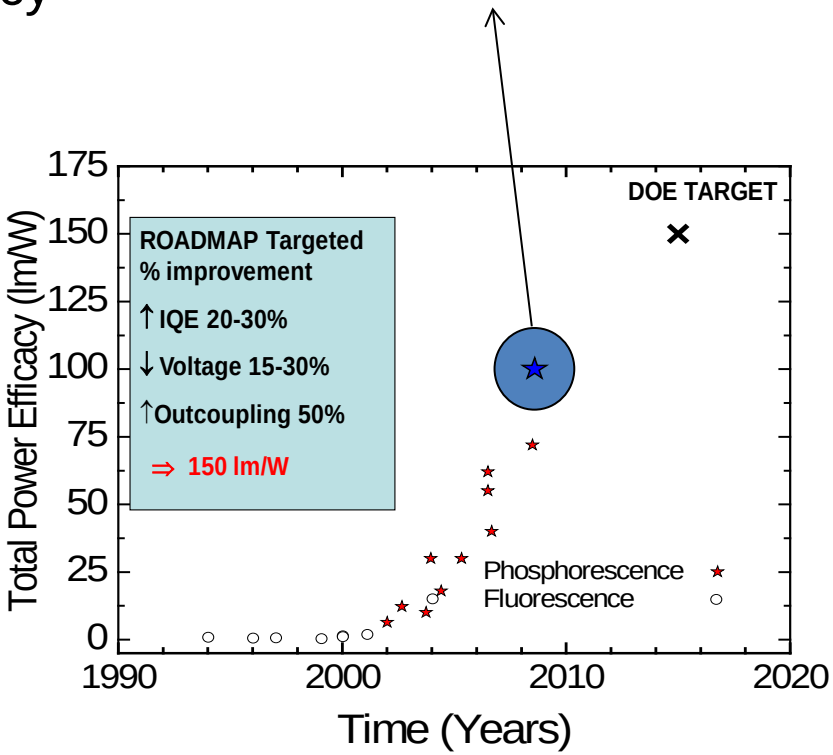


Chihaya Adachi, Kyushi Univ.

Φ_{int}~ 100%! Nature, 492, 234 (2012)

White OLEDs for solid state lighting

- Multiple color centers to achieve broad band white
  - Highest efficiency is for multilayer, three phosphor white
- Challenges
  - Achieving high efficiency for all colors
  - Low drive voltage at high efficiency
  - Low cost
    - Simple architecture
    - Ir → Cu or TADF
    - Substrate and TCO
    - Coating methods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