White Organic Light Emitting Diodes for Super-thin Flat Panel Lighting

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Outline
1. Why white OLED is necessary for lighting?
2. What is OLED?
3. How to make white OLEDs?

FNMA09 L’Aquila-Sulmona, September 28, 2009
electricity consumption in Japanese houses

Japanese Government report
Why OLED lighting and OLED displays are needed?
Because of **Shortage of Oil Resource**

![Graph showing oil production scenarios]

**Figure 2. Annual Production Scenarios with 2 Percent Growth Rates and Different Resource Levels (Decline R/P=10)**

- **USGS Estimates of Ultimate Recovery**
  - Probability
    - Low (95%): 2,246
    - Mean (expected value): 3,003
    - High (5%): 3,896

- **Decline R/P = 10**
  - 2047
  - 2026
  - 2037

**Source:** Energy Information Administration

*Note: U.S. volumes were added to the USGS foreign volumes to obtain world totals.*

No more oil after 40 years?

Low-energy consuming lighting and display are needed.
Power efficiency of lighting

power efficiency: \( \eta = \pi L(\text{cd})/J(A)V(V) \)

Incandescent lamp (100W): 16〜18 lm/W
Xe lamp: 25〜35 lm/W

Fluorescent lamp: 40〜110 lm/W

White LED (Cree, USA): 131 lm/W
White LED (Nichia, Japan): 150 lm/W

White OLED (Universal Display Corp., USA): 102 lm/W (2008.6.) at 1000cd/m²
White OLED (Novaled AG, Germany): 90 lm/W at 1000cd/m², with attachment 124 lm/W (2009.5.)

Problems:

LED: shortage of rare metals like In and Ga
Fluorescent lamp: containing Hg
Organic Electronics

Everything by organic materials

Displays
Electronic paper
Transistor, Condenser
Solar cell
Lasers: Easily tunable and any emitting color

New Lighting using white OLED

General Electric Global Research Co.

Fraunhofer Institut für Photonische Mikrosysteme (IPMS) in Dresden

OSRAM
Progress of TV displays

- **CRT-TV**
  - Contrast: 1,000,000:1

- **Liquid Crystal Display**
  - Contrast: 3,000:1

- **Plasma Display Panel**
  - Contrast: 8,000:1
  - Promising for large format displays
  - Basically fluorescent tubes
  - High-voltage discharge excites gas mixture (He, Xe)
  - Upon relaxation UV light is emitted
  - UV light excites phosphors
  - Large viewing angle

- **Organic Light emitting diode (OLED) display**
  - Thickness: 3 mm
  - Consumption power: 45 V
  - Contrast: 1,000,000:1

- **SONY OLED 11’ TV 「XEL-1」**
  - Dec., 2007
  - Contrast: 45 V

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*Note: The diagram shows a comparison between different types of TV displays, highlighting their properties and characteristics.*
Principle of LC Display

Orientation of LC is changed by applied voltage

Nematice liquid crystal

V=0

E(=V/d)

Incident Light

Electric field plane of light

polarizer

No light

Incident Light

Transmitted Light

polarizer

V

Polarizer  Twisted Nematic Cell  Polarizer

Incident Light

Blocked Light

Orientation of LC is changed by applied voltage
Advantage of OLED devices

1. Self-emission, No back-light
2. High response, wide viewing angle
3. High contrast image
4. Super-thin flat, lightweight
5. Flexible, paper-like display
6. Low voltage operation 5V: Low cost operation
7. Organic materials: Easy manufacturing
8. Low cost for production
Organic Light Emitting Diode (OLED) with organic semiconductors

Emission by Recombination of electron and hole: Electroluminescence

Inorganic LED

Kyoto Sangyo Univ.

Green and Red OLEDs

White OLEDs

Kyoto Sangyo Univ.
Actual OLED with multi-layers for carrier balance and confinement to make high density excitons

**Diagram:**
- **Cathode**
- **Electron injection layer**
- **ETL**
- **Emission layer**
- **HTL**
- **Hole injection layer**
- **Anode----ITO glass substrate**

**Guest-Host system**
- Emitter is doped in host: e.g. green Ir(ppy)$_3$ in CBP,
- red PtOEP in CBP,
- red DCM1 in Alq$_3$

**Electroluminescence EL**
- **Similar layers for different colors**
  - Green: Ir(ppy)$_3$ in CBP, red: PtOEP in CBP, red: DCM1 in Alq$_3$
confinement electrons and holes in emitting layer

Hole injection layer

Electron blocking layer

Emission by e-h recombination

Hole transport layer

Electron transport layer

Hole blocking layer

Electron injection layer

LUMO

HOMO

ITO

Hole injection layer

Electron blocking layer

Electron injection layer

Hole blocking layer

LUMO

HOMO

ITO

Electron injection layer

Electron transport layer

Hole blocking layer

LUMO

HOMO

ITO

Electron injection layer

Electron transport layer

Hole blocking layer

LUMO

HOMO

ITO
carrier hopping in HOMO and LUMO levels in amorphous semiconductor film

hole and then electron are trapped at dopant

Removal of electron from hole transport molecules $\alpha \rightarrow $NPD

$N \rightarrow N^+ + e$  $e + N^+ \rightarrow N$

$N: (1s)^2(2s)^2(2p)^3$
How to increase the quantum efficiency in OLED?

1. High numbers of injected electrons and holes in emitting layer
   - good injection layer
   - high carrier mobility materials
   - confinement of electrons and holes

2. Same number of electrons and holes because exciton is formed by $e+h$

3. All excitons should be used for emission
   Phosphorescent emitter is the best.

4. Emission should be taken outside from emitting layer inside of OLED efficiently
Electroluminescence spectra

Mono color

white color

PtOEP
(Platinum octaethylporphyrin)

Ir(ppy)$_3$
(tris(2-phenylpyridine) iridium)

Ir$_1$
Ir(ppy)$_3$
Pt$_2$
PtOEP

at 5 V

Electroluminescence (arb. units)
wavelength (nm)

emission intensity (arb. units)
wavelength (nm)

Mono color

white color

at 5 V

Electroluminescence (arb. units)
wavelength (nm)

emission intensity (arb. units)
wavelength (nm)
Currently available OLED displays

Cellar phone with OLEDs

Fujitsu F900i

F506i

Feb., 2004

May, 2004

Main LCD 262,144 colors 2.4“ TFT

Front OLED 4,096 colors 1.1“

Kodak Digital Camera

Kodak One-Seg OLED TV

SAMSUNG AMOLED TL320

12.2 Mega Pixels

LS433 LCD

LS633 OLED

Kodak Digital Camera

Kodak LS433 LCD

Kodak LS633 OLED

SAMSUNG AMOLED TL320

12.2 Mega Pixels
Currently used OLED display

Victor Co. Audio compo

Pioneer Co., Display panel for automobiles

portable audio player

Matsushita Co.,

Sony

Olympus
What lighting is good for us?

Materials should be seen under lighting just as seen under sun.

White light as sunshine
CRI color rendering index under sunshine CRI=100 (standard)

usual f. lamp CRI 60

3-λ f. lmap CRI 80

3-λ natural f. lmap CRI 90

color temperature: 2500-6000K
chromaticity index CIE (0.33, 0.33) CRI>80

http://map.answerbox.net/landmark-368647-bbs-2.htm
generation of white light

A. RBG parallel

B. White with RGB color filters

C. Color conversion: B to G, B to R

D. Tandem structure

E. Single emitting layer

R, B emission
R, G, B emission
Device A is much better than Device B.

3-layer emission due to Bepp2, Alq3, Rubrene

Z.Y. Xie et al, APL, 74(1999) 641

FIG. 1. Molecular structures of materials used and configuration for organic multiheterostructure white LEDs.

FIG. 2. EL spectra of (a) ITO/TPD(50 nm)/BePP₂(50 nm)/Al, (b) ITO/TPD(50 nm)/Alq₃(50 nm)/Al, (c) ITO/TPD(50 nm)/BePP₂:rubrene(50 nm)/Al, respectively.

FIG. 4. EL spectra of (a) ITO/TPD(50 nm)/BePP₂(5 nm)/TPD(4 nm)/BePP₂:rubrene(5 nm)/TPD(4 nm)/Alq₃(10 nm)/Al and (b) ITO/TPD(50 nm)/BePP₂(5 nm)/TPD(8 nm)/BePP₂:rubrene(5 nm)/TPD(8 nm)/Alq₃(10 nm)/Al.
3-Layer emission

Fig. 1. (a) EL spectra of WOLED device with different thin-NPB layer thickness under the applied voltage of 8 V. The corresponding CIE-1931 xy coordinates are (0.329, 0.368), (0.323, 0.315), and (0.321, 0.290) when the thickness of the thin-NPB is 2, 2.5, and 3 nm, respectively. With increased bias, the CIE-1931 xy coordinates of the device with a 3 nm thin-NPB layer are located nearest to the coordinates (0.333, 0.333). Inset, EL spectra from DPVBi (□), Alq3 (△), and DCJTBI (○), which were obtained with

\[
\text{CIE} = (0.33, 0.33)
\]

\[
\text{CCT} \, (\text{correlated color Temp.}) = 2500-6000 \, K
\]

\[
\text{CRI} \, (\text{color rendering index}) > 80
\]

<table>
<thead>
<tr>
<th>Applied Bias (V)</th>
<th>CIE Coordinates</th>
<th>CCT (K)</th>
<th>CRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.321 0.290</td>
<td>6014</td>
<td>80.9</td>
</tr>
<tr>
<td>9</td>
<td>0.315 0.299</td>
<td>6673</td>
<td>84.8</td>
</tr>
<tr>
<td>10</td>
<td>0.313 0.302</td>
<td>6714</td>
<td>85.8</td>
</tr>
<tr>
<td>11</td>
<td>0.318 0.320</td>
<td>6305</td>
<td>88.3</td>
</tr>
<tr>
<td>12</td>
<td>0.327 0.336</td>
<td>5804</td>
<td>90.2</td>
</tr>
</tbody>
</table>

High external efficiency from POLED with three small molecules

**WOLED1; 16.6 %**  
**WOLED2; 6.0%**

Flr6: bis(40,60-difluorophenylpyridinato) tetrakis(1-pyrazolyl)borate  
PQIr: Ir(III) bis(2-phenylquinolyl-N,C20) acetylacetonate

Reducing hole mobility for charge balance, Uniform distribution of holes and electron. Ambipolar host for uniform exciton formation across the entire EML

OLEDs with Exciplex emission
Exciplex emission

4,4’,4”-tris[3-methylphenyl-1(phenyl)amino] triphenylamine (m-MTDATA): hole-transport material:

\[ M \rightarrow M^+ + e \]

4,7 dipheny-1,10-phenanthroline (Bphen): electron-transport material:

\[ B + e \rightarrow B^- \]

6620 cd/m² at 8.7 V

\[ M^+ + B^- \rightarrow (MB)^* \rightarrow MB + h\nu \]

emission from interface


No emission from Bphen monomer
White OLED with exciplex and monomer


2000 cd/m²
0.58 lm/W
CIE (0.31,0.35)
White OLED using only exciplex

Four exciplexes in a device

Intralayer exciplex

Boundary exciplex

m-MTDATA

LUMO 2.0 eV

HOMO 5.1 eV

m-MTDATA

ML-1 (x nm) 3.2 eV

Al(DBM)_3

ML-2 (10 nm) 2.3 eV

TPD

Bphen

2.5 eV

Bphen

6.0 eV

LiF/Al

Al(DBM)_3

acceptor

donor
Increase of Intralayer exciplex

Decrease of R: Decrease of m-MTDATA Decrease of red exciplex

Table 1 CIE coordinates, CCT, and CRI of the WOLED device with x=3 nm and R=1

<table>
<thead>
<tr>
<th>Bias voltage (V)</th>
<th>CIE coordinates (x, y)</th>
<th>CCT (K)</th>
<th>CRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>(0.36, 0.37)</td>
<td>4593</td>
<td>94.0</td>
</tr>
<tr>
<td>10</td>
<td>(0.33, 0.35)</td>
<td>5477</td>
<td>94.1</td>
</tr>
<tr>
<td>12</td>
<td>(0.32, 0.35)</td>
<td>6100</td>
<td>93.6</td>
</tr>
<tr>
<td>14</td>
<td>(0.31, 0.35)</td>
<td>6571</td>
<td>92.5</td>
</tr>
</tbody>
</table>
Multi-coloration by single molecule

Excimer

Mixed ligand molecule
Single dopant WOLED with Excimer emission

\[ M^*M \rightarrow M + M + \text{hv} \]

**Excimer**

\( \text{N}^\text{C}^\text{N-Pt(Cl)} \)

12% 6% 3%

[Image of EL intensity curve]

**Pt compounds: plane structure, stacking**

\( \text{N}^\text{C}^\text{N-Pt(Cl)} \)

**Cyclometalated Pt\(^{2+}\)-compounds**

\[ \text{QE} = 6.1\% \text{, CRI}=73 \text{, CIE}=(0.32, 0.39) \text{, 11.8 lm/W (at 1cd/m2)} \]

polymer or small molecule?

**Polymer:**

- Spin-coating, wet-process: cheap, easy, simple structure (2-layer), and ink-jet possible (for mass-production)

**Small molecule:**

- Thermal evaporation in vacuum
### Polymer White OLEDs

**A. Dispersion type (doping, blend, guest-host)**

<table>
<thead>
<tr>
<th>dopant</th>
<th>host</th>
<th>emitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL small molecule</td>
<td>FL polymer</td>
<td>Dopant</td>
</tr>
<tr>
<td>PL small molecule</td>
<td>FL polymer</td>
<td>Dopant</td>
</tr>
<tr>
<td>FL polymer</td>
<td>FL polymer</td>
<td>Dopant</td>
</tr>
<tr>
<td>PL polymer</td>
<td>FL polymer</td>
<td>Dopant+host</td>
</tr>
<tr>
<td>PL polymer</td>
<td>PL polymer</td>
<td>Dopant+host</td>
</tr>
</tbody>
</table>

FL: Fluorescent  
PL: Phosphorescent

**B. Single polymer**

<table>
<thead>
<tr>
<th>non-copolymer</th>
<th>emitter</th>
<th>host</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-copolymer</td>
<td>Monomer+Excimer</td>
<td>FL polymer</td>
</tr>
<tr>
<td>Non-copolymer</td>
<td>Monomer+Electromer</td>
<td>FL polymer</td>
</tr>
<tr>
<td>Blended in backbone, copolymer</td>
<td>Monomer</td>
<td>PL polymer</td>
</tr>
<tr>
<td>Blended in side-chain, copolymer</td>
<td>Monomer</td>
<td>PL polymer</td>
</tr>
</tbody>
</table>
Guest polymer + host polymer

\[
\begin{align*}
\text{polyperiren-ethylbenzen} & \text{dopant} \\
0.05\text{wt\% PPDB} & \\
\text{m-LPPP (ladder-type paraphenyrene)} & \\
\text{host}
\end{align*}
\]

Ext. Effic: 1.2 %, CIE(0.31, 0.33)

ITO/ 0.05%PPDB:m-LPPP /Al

Doped WPLED: Polymer-doped polymer

Carrier balanced green polymer

M. Suzuki (NHK) et al, APL 86(2005)103507


c<sub>f</c> S. Lamansky et al, JACS123('01)4304: 
Ir<sub>s</sub>(ppy)<sub>s</sub>(acac) in CBP host, multi-layer OLED
12.3%, 38 lm/W, >50 Cd/A

η<sub>ext</sub>=11.8% at 0.12mA/cm<sup>2</sup>,

power effi.= 38.6 lm/W at 0.02mA/cm<sup>2</sup>
with Cs e-injector

<table>
<thead>
<tr>
<th>Polymer</th>
<th>TPD: PBD: Ir&lt;sub&gt;s&lt;/sub&gt;(ppy)&lt;sub&gt;s&lt;/sub&gt;(acac)</th>
<th>Electron-injection layer</th>
<th>η&lt;sub&gt;ext&lt;/sub&gt;(%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>η&lt;sub&gt;power&lt;/sub&gt;(lm/W)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>55: 41: 4</td>
<td>Ca</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>B</td>
<td>34: 62: 4</td>
<td>Ca</td>
<td>3.9</td>
<td>6.3</td>
</tr>
<tr>
<td>C</td>
<td>18: 79: 3</td>
<td>Ca</td>
<td>6.8</td>
<td>11.6</td>
</tr>
<tr>
<td>C</td>
<td>18: 79: 3</td>
<td>Ba</td>
<td>9.7</td>
<td>19.4</td>
</tr>
<tr>
<td>C</td>
<td>18: 79: 3</td>
<td>Cs</td>
<td>11.8</td>
<td>38.6</td>
</tr>
</tbody>
</table>

<sup>a</sup>Maximum value.
Guest-Host system or Non-doped system?

Non-dopant system is much better than guest-host system

*Because*

1. Best concentration is 1-2% dopant, difficult to control it within ±0.5% in mass produced OLEDs

2. For White OLED, blue-green-red stacking layered OLED gives rise to energy transfer from blue to green to red layer, color instability
Single polymer WOLEDs

polymer

Backbone copolymer

Side-chain copolymer

Mono-dopant polymer

monomer

Excimer

Electromer
Single backbone copolymer


PF: Polyfluoren, a bipolar charge-tranporting PF derivative

4,7-Bis(9,9-dihexylfluoren-2-yl)-2,1,3-benzothiadiazole (GM)

4,7-Bis[5-(9,9-dihexylfluoren-2-yl)thiophen-2-yl]-2,1,3-benzothiadiazole (RM). Using the procedure described for GM, the

Figure 2. Absorption and PL spectra of PFTO-I and WPFTO-I (a) dilute CHCl₃ solutions and (b) the solid state.

Figure 3. PL spectrum of PFTO in the solid state and the PL and absorption spectra of GM and RM in dilute CHCl₃ solutions.

4. EL spectra of the devices incorporating PFTO-I or WPFTO-I emitting layer at an applied potential of 9 V.
Different dopant: red-emitter 2,1,3-benzothiadiazole-incorporated blue-polymer

\[ \text{8.99 cd/A, 5.75 lm/W, } \eta = 3.8\% \]
\[ \text{c.f. 3.8 cd/A, 2.0 lm/W, } \eta = 1.50\% \]


Figure 5. Electroluminescence spectra of single layer devices (ITO/PEDOT:PSS/polymer/Ca/Al) of the polymers.
赤色発光： フェニルキノリンIr錯体Phq発光分子
緑色発光： ベンゾチアヂアゾルBTの発光分子
青色発光： 発光分子基はフルオレンPFの発光分子

パワーエレクトリシティ 1.9cd/A、最高輝度3585cd/m²

<table>
<thead>
<tr>
<th>Copolymer</th>
<th>Bias [a]</th>
<th>J [a]</th>
<th>LE [a]</th>
<th>L_max [cd m⁻²]</th>
<th>CIE [b]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[V]</td>
<td>[mA cm⁻²]</td>
<td>[cd A⁻¹]</td>
<td></td>
<td>(x, y)</td>
</tr>
<tr>
<td>PFBT05-Phq2</td>
<td>6.8</td>
<td>2.5</td>
<td>2.8</td>
<td>2170</td>
<td>(0.34, 0.3)</td>
</tr>
<tr>
<td>PFBT1-Phq2</td>
<td>6.7</td>
<td>5.6</td>
<td>1.9</td>
<td>3585</td>
<td>(0.34, 0.3)</td>
</tr>
<tr>
<td>PFBT3-Phq2</td>
<td>7.4</td>
<td>5.2</td>
<td>1.8</td>
<td>2410</td>
<td>(0.32, 0.3)</td>
</tr>
<tr>
<td>PFBT5-Phq2</td>
<td>6.3</td>
<td>2.2</td>
<td>6.1</td>
<td>10110</td>
<td>(0.32, 0.4)</td>
</tr>
<tr>
<td>PFBT1-Phq1</td>
<td>6.4</td>
<td>3.4</td>
<td>3.6</td>
<td>6280</td>
<td>(0.26, 0.2)</td>
</tr>
<tr>
<td>PFBT1-Phq4</td>
<td>6.0</td>
<td>3.1</td>
<td>4.7</td>
<td>5309</td>
<td>(0.38, 0.3)</td>
</tr>
<tr>
<td>PFBT1-Phq5</td>
<td>5.9</td>
<td>1.5</td>
<td>5.6</td>
<td>6440</td>
<td>(0.44, 0.3)</td>
</tr>
<tr>
<td>PFBT3-Phq3</td>
<td>6.4</td>
<td>2.3</td>
<td>4.6</td>
<td>6035</td>
<td>(0.31, 0.3)</td>
</tr>
</tbody>
</table>

White light using color conversion method

**Green** (515 nm) phosphorescence emitter: Ir(ppy)$_3$

ITO/α-NPD/6.2mol% Ir(ppy)$_3$;TCTA/CF-X/Alq$_3$/LiF/Al

TCTA host; $\eta_{\text{ext}} = 19.2\%$  
M. Ikai et al., APL 79 (2001)156.

**Blue** (465nm) phosphorescence emitter: Firpic

ITO/CuPc/α-NPD/6%FIrpic:host/BAIq/LiF/Al

CBP host; $\eta_{\text{ext}} = 6.1\%, 7.7$ lm/W

mCP host; $\eta_{\text{ext}} = 7.5\%, 8.9$ lm/W  
External quantum efficiency

\[ \eta_{\text{ext}} \% = \gamma \eta_{\text{ex}} \eta_{r} \eta_{\text{out}} \]

\( \gamma \): carrier injection balance
\( \eta_{\text{ex}} \): exciton formation efficiency
\( \eta_{r} \): exciton recombination efficiency
  - 0.25 for singlet exciton, 1.0 for triplet exciton
\( \eta_{\text{out}} \): outcoupling effi. for light from OLED
  \( \eta_{\text{out}} \sim 1/2n_{a}^{2} \) (=20%)

Phosphorescent emitters
  \( \eta_{\text{int}} = 100\% \), \( \eta_{\text{ext}} \% = 20 \% \)
Host materials for blue emitters

Currently very weak efficiency

ITO/CuPc/α-NPD/6%Flrpic:host/BAIq/LiF/Al

CBP: **6.1%**, 7.7 lm/W

mCP: **7.5%**, 8.9 lm/W


Highly stable (high glass transition temp.), high carrier mobility, high $T_1$ energy level hosts are necessary.
The best host material for blue emitter in OLEDs is **bis(3,5-di(9H-carbazol-9-yl)phenyl)diphenylsilane** (SimCP2).

### Electrical Properties

- **SimCP2**: Tg = 148°C
- **mCP**: 55°C
- **SimCP**: 101°C
- **CBP**: 62°C

### Photophysical Properties

- **SimCP2**
  - HOMO: 6.12 eV
  - LUMO: 2.56 eV

### Photoluminescence (PL)

<table>
<thead>
<tr>
<th>PL Intensity (normalized)</th>
<th>Lamp Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>non-annealed</td>
</tr>
<tr>
<td>2</td>
<td>70°</td>
</tr>
<tr>
<td>3</td>
<td>120°</td>
</tr>
<tr>
<td>4</td>
<td>150°</td>
</tr>
</tbody>
</table>

### Power Efficiency

- **η<sub>ext</sub>** of **17.7%** and power efficiency of **24.2 lm/W** at 100 cd/m² for FIrpic: 
  ITO/PEDOT:PSS(35nm)/14 wt% FIrpic:SimCP2(35nm)/TPBi(28nm)/LiF/Al

  c.f., 10.4 and 5.9 lm/W in the case of SimCP and mCP hosts, respectively

Copolymer with Rare-earth-complex organic molecules

Novel ternary copolymer containing both Tb(III) and Eu(III) complexes for white-light electroluminescence

M. J. YANG, L. C. ZENG, Q. H. ZHANG
Department of Polymer Science and Engineering, Zhejiang University, Hangzhou, People's Republic of China
E-mail: yangmi@cmsce.zju.edu.cn

high color purity with sharp lines
White OLED with rare-earth small molecules

Small molecule: Dual emission from a single molecule

Ir(dfppy)$_2$(pq)
Ir(dfppy)$_2$(acac): 469nm PL
Ir(pq)$_2$(acac): 597nm PL

Max: 11.0 cd/m$^2$, 5.60 lm/W