Vacuum Deposited Organic Light Emitting Devices on Flexible Substrates

"what a long, strange trip it's been"

Final Program Review
Princeton University

May 3, 2002

Vacuum Deposited Organic Light Emitting Devices on Flexible Substrates

Support: DARPA (F33615-94-1-1414)

Program Managers: Gurdial Saini & Darrel Hopper

Agent: Wright Patterson AFB

Dates: 6/13/94 - 4/30/02

Team:

Princeton University (S. Forrest)
HRL (K. Sayyah) - End Dec. 31, 00
Universal Display Corporation (J. J. Brown) - End Dec. 31, 00
University of Southern California (M. E. Thompson)

Program Objective

Demo PM & AM flexible displays by pushing the state of the art in OLED technology using SOLEDs, FOLEDs, OVPD, lasers and organic transistors.

Team Responsibilities

- **Princeton:** Develop flexible, transparent, stacked and ultrahigh efficiency OLEDs and packaged display pixel arrays. Initial reliability testing. Organic transistors and roll-to-roll processing demonstrations.
- **USC:** Organic materials development for high reliability, efficient, saturated color.
- **HRL:** Si TFT AM development on glass and flexible substrates using lift-off. Qualification for DoD and civilian applications.
- **UDC:** Reliability studies of AM & PM flexible displays. Display manufacturing development and scale-up. Formation of strategic alliances.

Specific Objectives

- **Demo. flexible, ultralight weight, AM displays. (x)**
- **Demo. RGB SOLED pixel with true color (√)**
- **Demo. high efficiency OLEDs with luminescence in the R, G & B using vacuum-deposited organics (√)**
- **Demo. scalability to large substrates (√)**
- **Demo. photolith patterning of high resolution pixels (√)**
- **Demo. OLED reliability (√)**
- **Demo. organic-TFTs for displays**
- **Develop methods to select optimal materials for high efficiency displays (√)**
- **Refine processes for prototype and manufacture (√)**

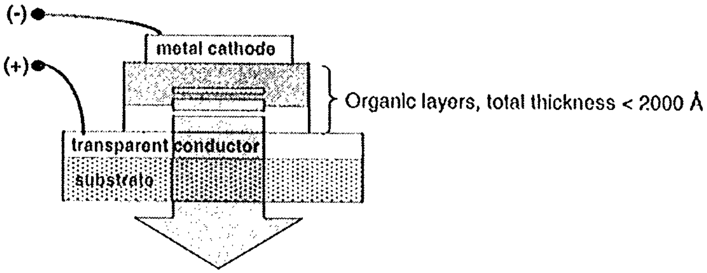
Accomplishments

- **Demo'd transparent, true color patterned SOLEDs**
  - √ Developed full, *quantitative* understanding of microcavity effects
- **Demo'd efficient R, G, B color emission**
  - √ Demo'd electrophosphorescent efficiencies in red and green (19%, int. eff. ~87%)
  - √ Demo'd phosphor-sensitized fluorescence with efficiencies of 8%.
  - √ Extremely long operational lifetimes found for some phosphors
- **Demo'd efficient TOLEDs for head-up, integrated apps.**
- Tech. transfer to UDC (facility on line) & HRL
- **Demonstrated method for micropatterning of displays: cold-welding followed by lift-off**
- **Demonstrated growth of OLEDs via OVPD**
  - √ **Equipment manufacturer building large scale production tools**

Technology Transfer

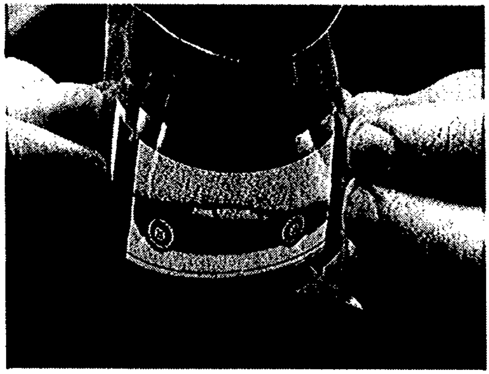
- **~40 Patents pending**
  - √ Architectures, materials, packages, phosphorescence, transistors, patterning
  - √ ~50 issued: FOLED, TOLED and SOLED parent case, phosphorescence, patterning, laser, vacuum and OVPD deposition basic patents.
  - √ All patents filed globally, with exclusive rights to UDC.
- **Established strong ties with potential manufacturers of equipment and panels**
- **Prototyping and Tech. Transfer facility opened by Universal Display- Significant resource leveraging and customer interest**

Benefits of OLEDs



- **can be prepared on any substrate - active materials are amorphous**

Flexible, Passive Matrix OLED Display



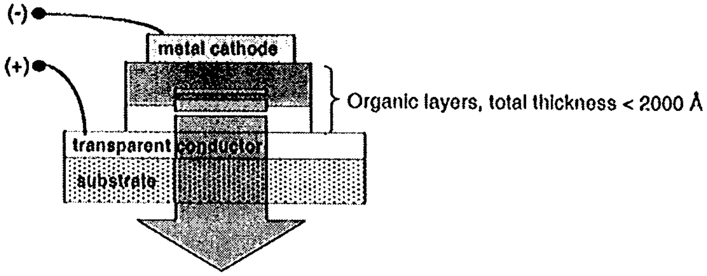
Courtesy: Universal Display Corp.

Flexibility is a transformational advantage of OLEDs.

But significant challenges remain:
  Lifetime must improve
  Conformal vs flexible
  Mechanical ruggedness

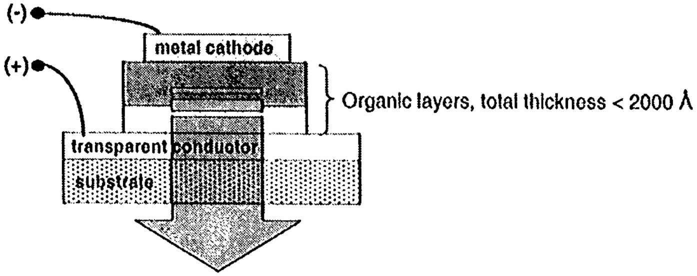
128x64 pixels, 400x500μm each
Display dimension: 2"x3"
Full motion video

Benefits of OLEDs



- low cost materials and fabrication methods, scalable to large area

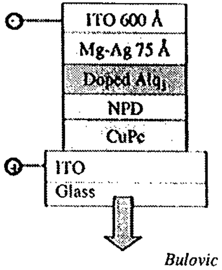
Benefits of OLEDs



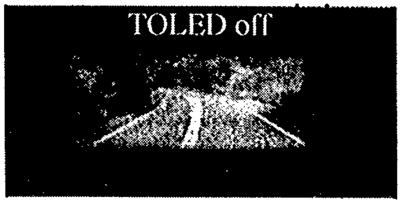
- readily tuned color and electronic properties *via* Chemistry
- can be transparent when off

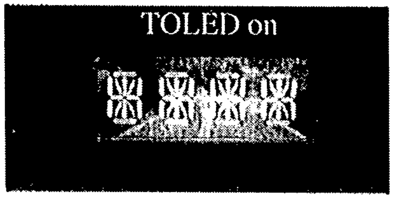
Transparent OLEDs (TOLEDs)

- Devices can be > 90% transparent
- Thin metal or electron injection layer is capped with ITO
- Transparent cathode can also be used

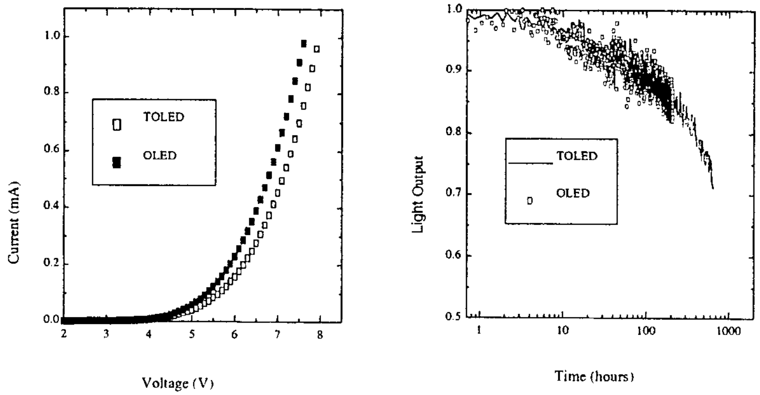


Bulovic et. al., Nature 1996





TOLED Current-Voltage and Lifetime Characteristics

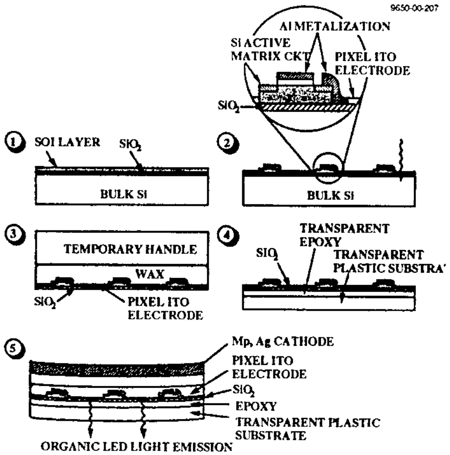


Sony 13 inch AMOLED-TFT Display

800x600 pixels
Full Color
Top emission

LABORATORIES

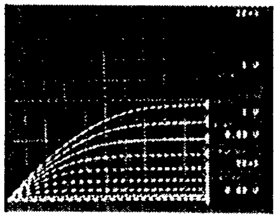
Schematic of Flexible AM-OLED Fabrication Process



LABORATORIES

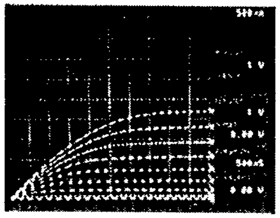
Characterization of Bonded-SOI PMOS Transistors (2)

- PMOS Bonded-SOI I-V Characteristics



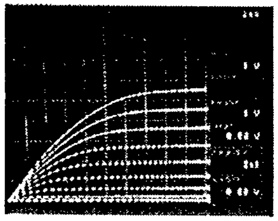
$L_G = 10\ \mu m$; $W_G = 5\ \mu m$

$I_{SD} = 97\ \mu A$
$V_{SD} = 10\ V$
$V_{SG} = 10\ V$



$L_G = 10\ \mu m$; $W_G = 100\ \mu m$

$I_{SD} = 2.2\ mA$
$V_{SD} = 10\ V$
$V_{SG} = 10\ V$

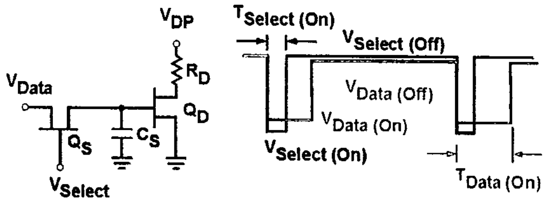


$L_G = 10\ \mu m$; $W_G = 500\ \mu m$

$I_{SD} = 11.0\ mA$
$V_{SD} = 10\ V$
$V_{SG} = 10\ V$

HRL LABORATORIES

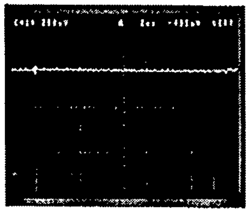
Characterization of Bonded-SOI Two Transistor Active Matrix Circuit (Resistor Load)



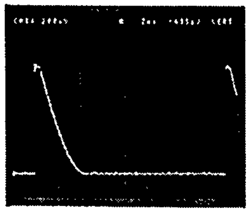
Wafer	C_S [pF]	$\Delta I_L/I_L(O)$
A-1	0.5	2%
A-1	1.1	<1%
A-1	11.0	<0.5%
A-2	0.5	<1%
A-2	1.1	<1%
A-2	11.0	<0.5%
A-3	0.5	2%
A-3	1.0	<0.5%
A-3	11.0	<0.5%
A-4	0.5	3%
A-4	1.1	2%
A-4	11.0	<0.5%
A-5	0.5	<0.5%
A-5	1.1	<0.5%

$V_{Select\ (On)} = -12$ V　$C_S = 0.5$ pF　$V_{Data\ (On)} = -10$ V

$T_{Select\ (On)} = 100\ \mu s$　$T_{Frame} = 16$ ms　$T_{Data\ (On)} = 500\ \mu s$

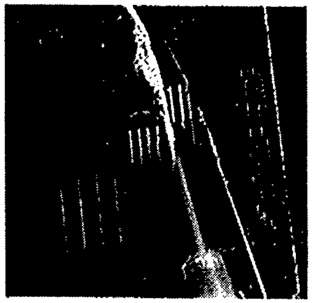


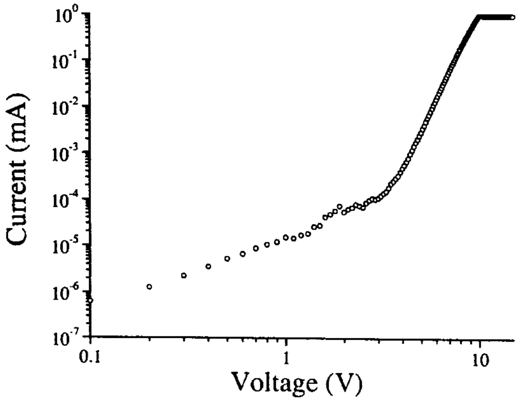
$V_{Select\ (Off)} = 0$ V



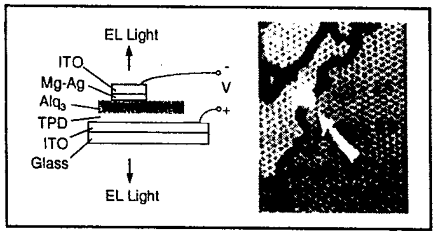
$V_{Select\ (Off)} = -1.6$ V

Data Summary for TOLEDs on Hughes Si

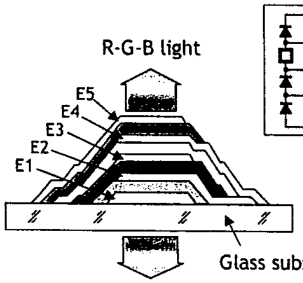


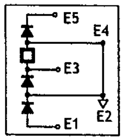


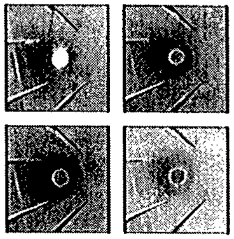
Transparent & Stacked Organic Light Emitting Devices for Full Color Generation



V. Bulovic, et al, *Nature*, **380** 29 (1996)

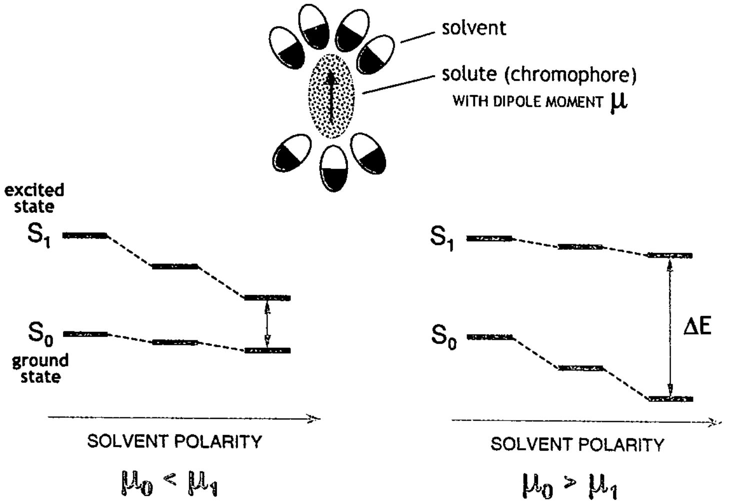






G. Parthasarathy, et al., *Adv. Mater.*, **11**, 907 (1999).

Influence of μ_0 and μ_1 on Chromatic Shift Direction



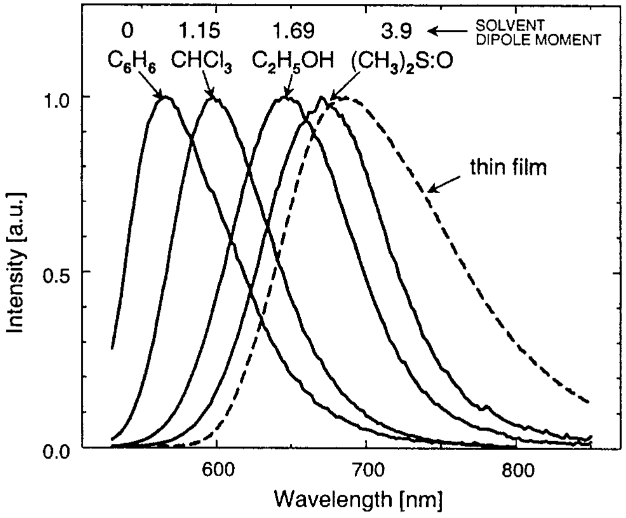
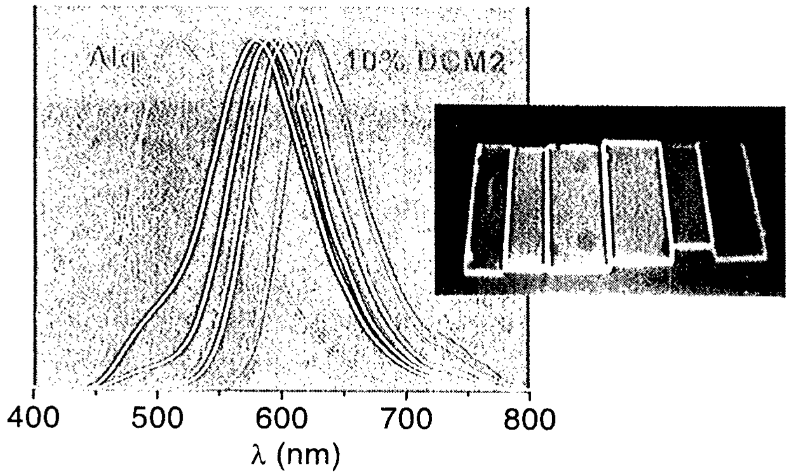
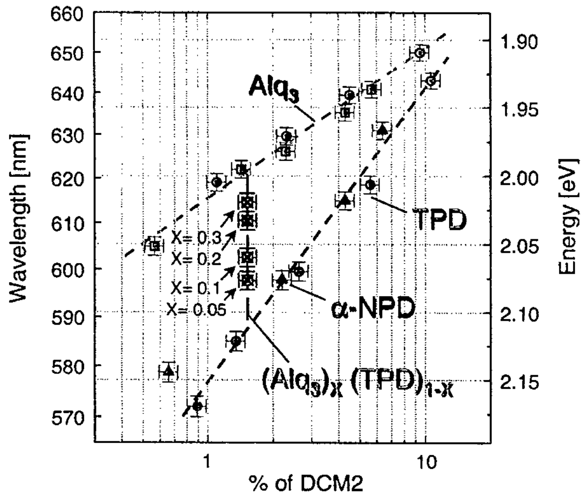


Figure 3, Bulovic *et al.*



Peak EL of DCM2 in Different Hosts

Bulovic et al., *Chem. Phys. Lett.* submitted (1999).



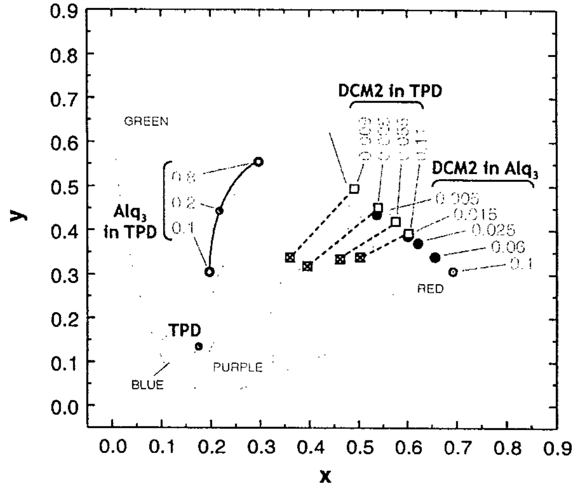
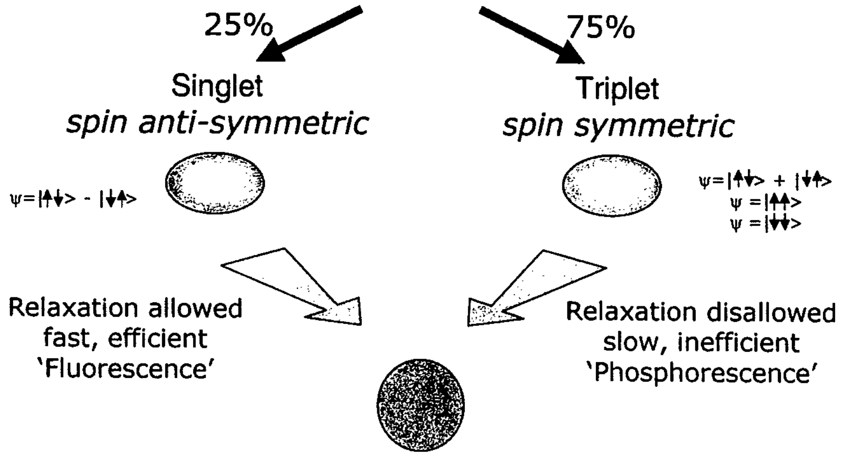


Figure 9, Bulovic *et al.*

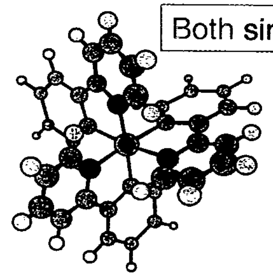
MOLECULAR EXCITED STATES AFTER ELECTRICAL EXCITATION



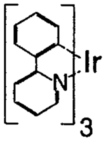
MOLECULAR GROUND STATE
spin anti-symmetric

Phosphorescence enhanced by mixing the singlet and triplet excited states
eg: spin orbit coupling via heavy metal atom (Pt or Ir)

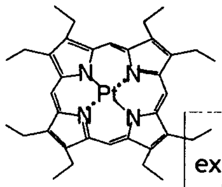
Both singlets **and** triplets are harvested!



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

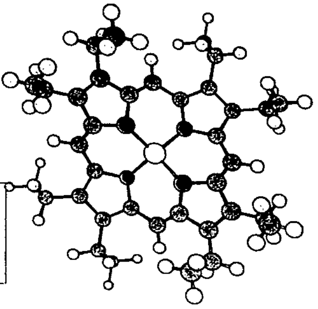


green emission
external quantum efficiency ~19%
phosphorescent lifetime ~0.5μs

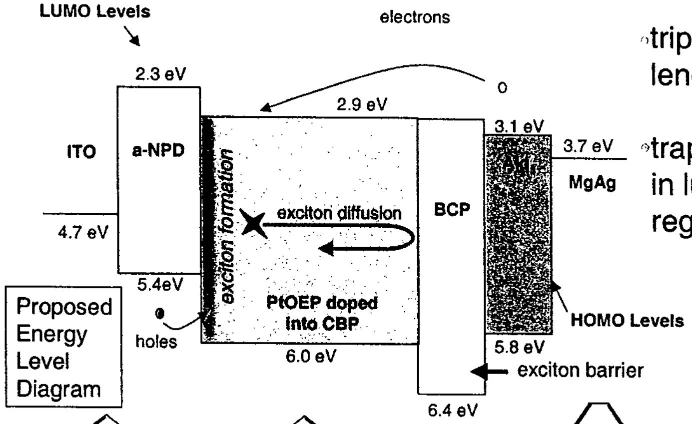


platinum octaethylporphyrin
PtOEP

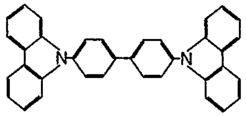
red emission
external quantum efficiency ~6%
phosphorescent lifetime ~70μs



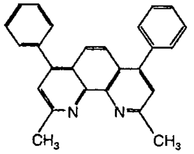
Electrophosphorescent device structure



- triplet diffusion lengths >100nm
- trap triplets in luminescent region



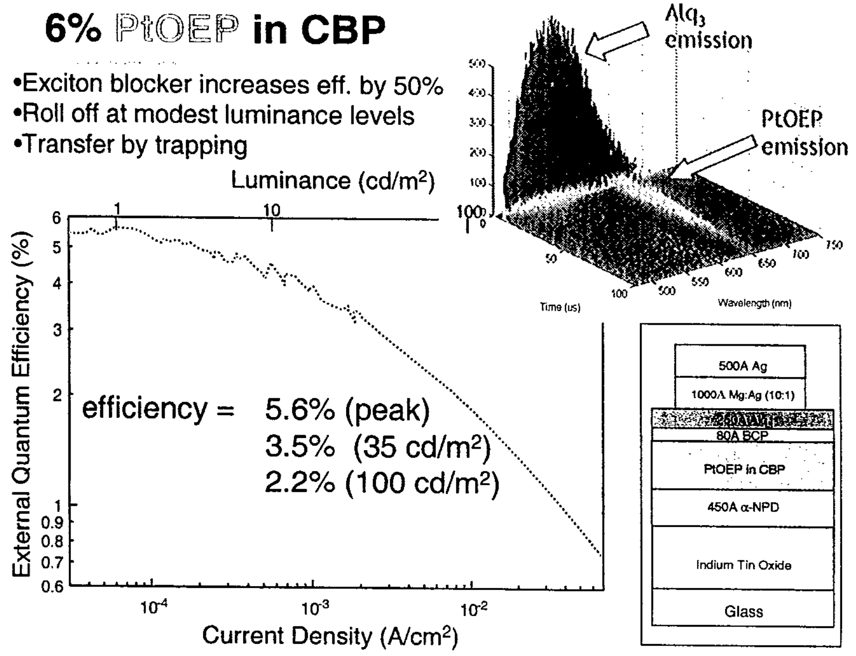
CBP



BCP

6% PtOEP in CBP

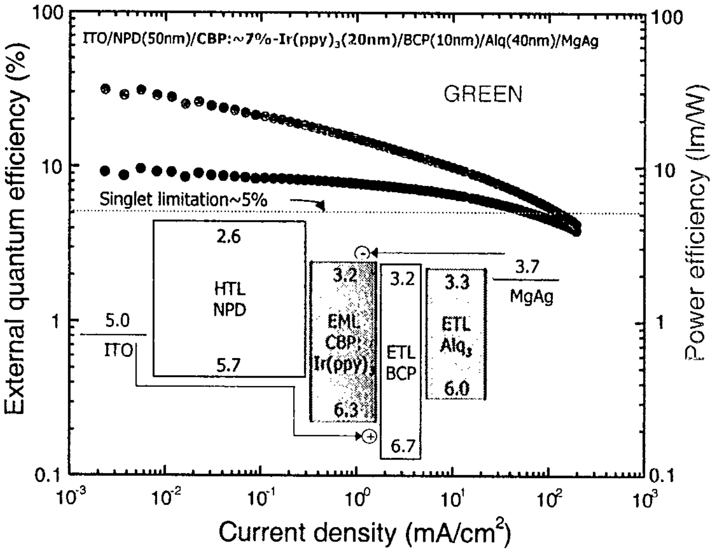
- Exciton blocker increases eff. by 50%
- Roll off at modest luminance levels
- Transfer by trapping

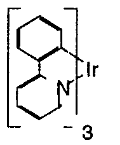


efficiency = 5.6% (peak)
3.5% (35 cd/m^2)
2.2% (100 cd/m^2)

$Ir(ppy)_3$ doped into CBP-HTL

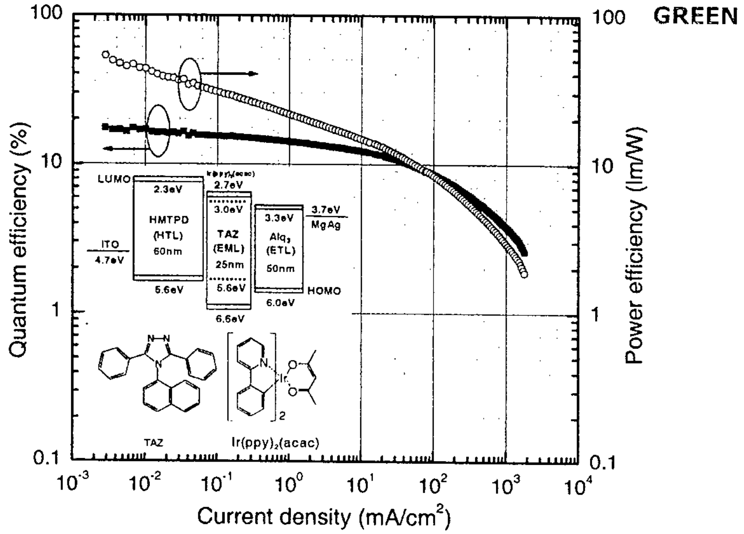
Baldo et al. Appl. Phys. Lett.,75,4(1999)



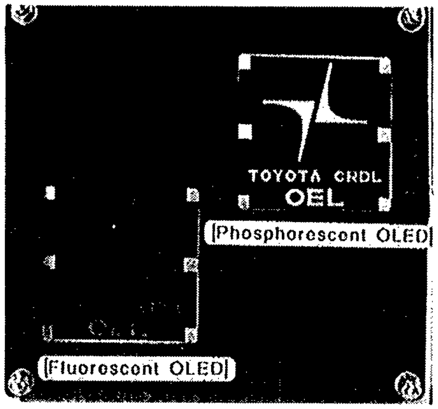


short lifetime: 2µs in toluene, 500ns in CBP

$Ir(ppy)_2(acac)$ doped ETL (Triazole) (η_{ext}=19%, η_{int}=87%)



OLED panels of fluorescence and phosphorescence



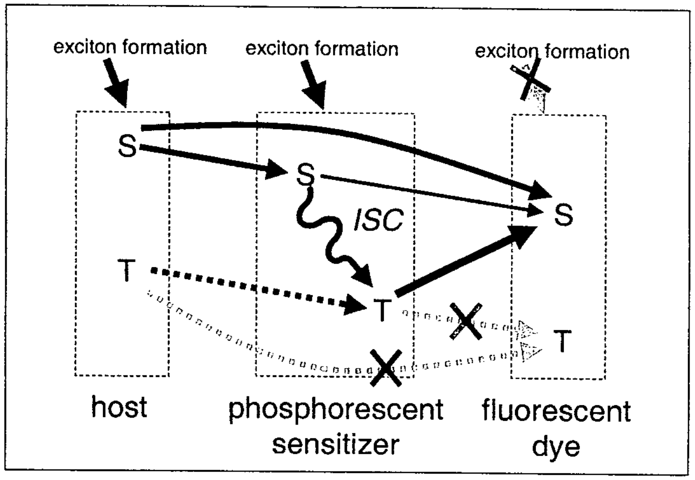
Conventional OLED Phosphorescent OLED

2001 MRS spring meeting, San Francisco, Paper C4.3

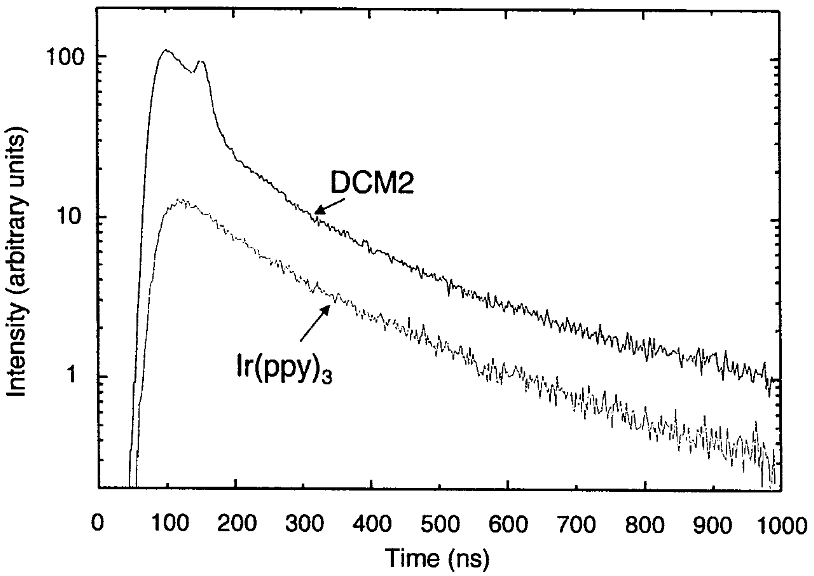
TOYOTA CENTRAL R&D LABS., INC.

TRIPLET-SINGLET TRANSFER

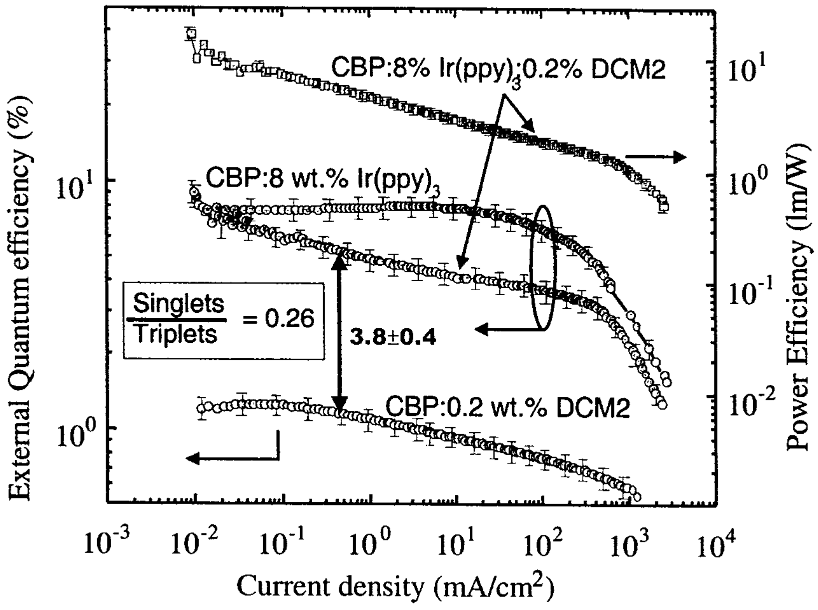
- ◇ Need separation between phosphorescent donor and fluorescent acceptor to prevent direct Dexter transfer to fluorescent triplet state
- ◇ Transfer possible for radiative triplet states



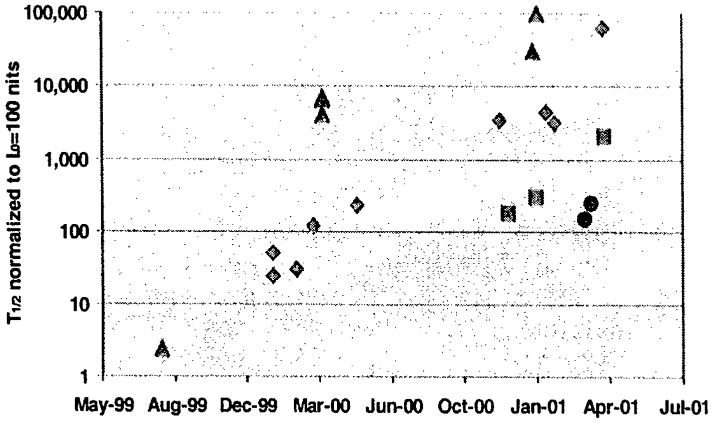
OLED Transient Response



- ◇ Delayed DCM2 fluorescence confirms sensitizing action of $Ir(ppy)_3$



Phosphorescent OLED Lifetime



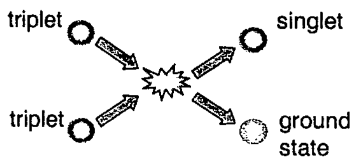
UNIVERSAL DISPLAY CORPORATION

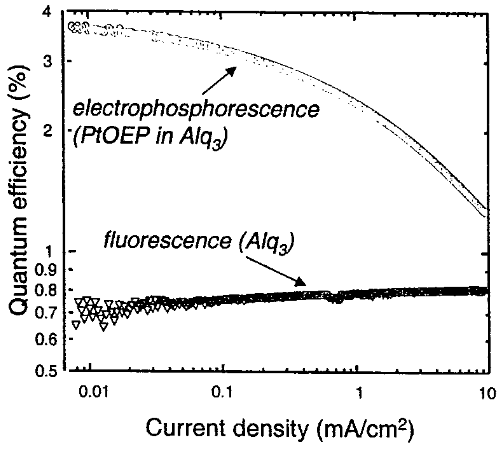
PHOSPHORESCENT EFFICIENCY DEGRADES WITH CURRENT DENSITY

Is it saturation of phosphorescent sites?

Current densities too low. Should be proportional to $1/J$ but actually closer to $1/\sqrt{J}$.

Or T-T annihilation?





Can the degradation be minimized?

THEORY

T-T annihilation destroys two triplets and creates a singlet

$$^3M^* + {}^3M^* \rightarrow {}^1M^* + M$$

Transient model: $\frac{d\left[{}^3M^*\right]}{dt} = -\frac{\left[{}^3M^*\right]}{\tau} - k_q\left[{}^3M^*\right]^2 + \frac{J}{qd}$

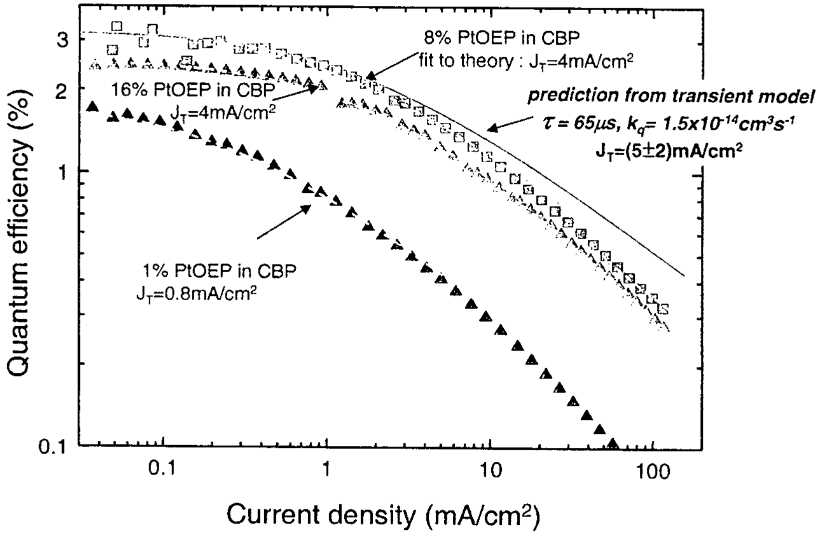
τ: triplet lifetime
k_q: T-T annihilation rate
J: current density
d: thickness of active layer

Transient solution: $\left[{}^3M^*(t)\right] = \frac{\left[{}^3M^*(0)\right]}{\left(1+\left[{}^3M^*(0)\right]\tau k_q\right)e^{t/\tau} - \left[{}^3M^*(0)\right]\tau k_q}$

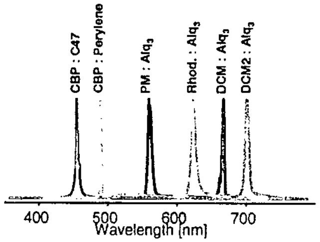
Steady state solution: $\frac{\eta}{\eta_0} = \frac{J_T}{4J}\left(\sqrt{1+8\frac{J}{J_T}}-1\right)$ η: quantum efficiency
η_0: max efficiency

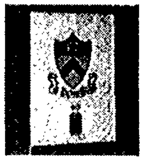
Threshold current density: $J_T = \frac{2qd}{k_q\tau^2}$
(for $\eta=\eta_0/2$)

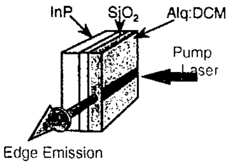
PREDICTION FROM TRANSIENT MODEL MATCHES MEASUREMENT



Organic Lasers

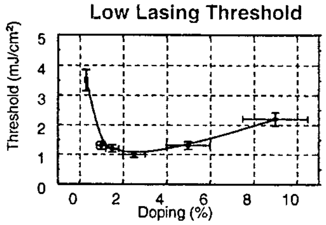


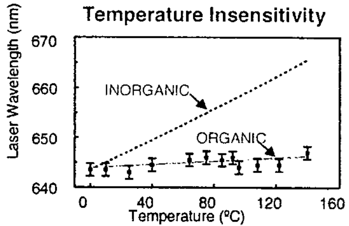




Kozlov, *et al.*, *Nature* 389, 362 (1997).

Motivation
- Material Tunability
- Freedom from Epitaxial Limitations
- Natural Quantum Dots

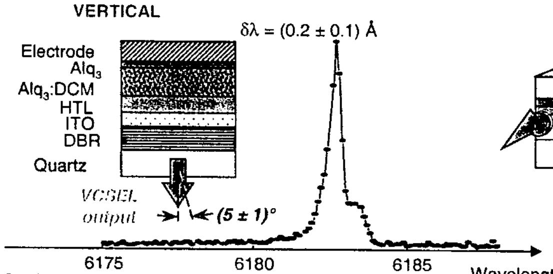




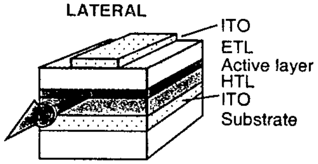
Kozlov, *et al.*, *Appl. Phys. Lett.* 71, 2575 (1997)

Organic Lasers

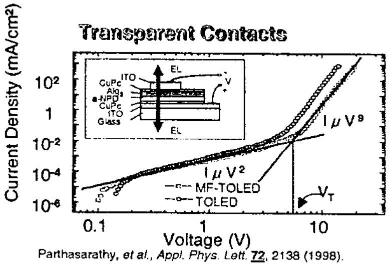
Electrically Pumped Structures



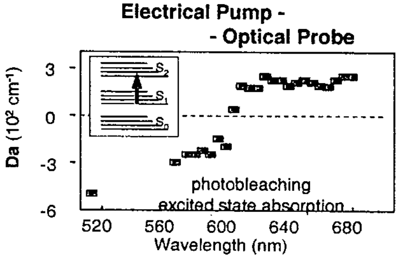
Bulovic, *et al.*, *Science* 279, 553 (1998).



need understanding of
- high injection transport
- contacts

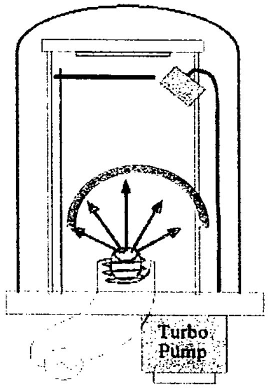


Parthasarathy, *et al.*, *Appl. Phys. Lett.* 72, 2138 (1998).



Vacuum Deposition

10^{-6} - 10^{-11} Torr



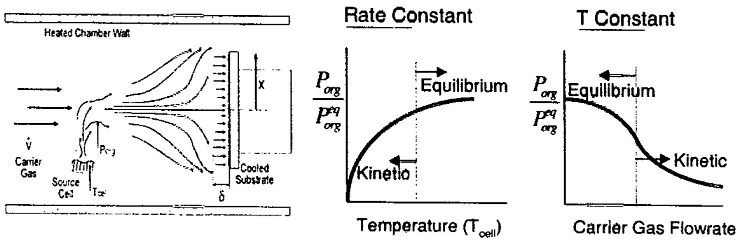
Advantages
- Simple
- Precise (monolayer) thickness control

Disadvantages
- Inefficient use of material
- Difficult to control dopant concentration
- Uneven deposition rate
- Chamber contamination and dust

⇨ Difficult to scale-up throughput

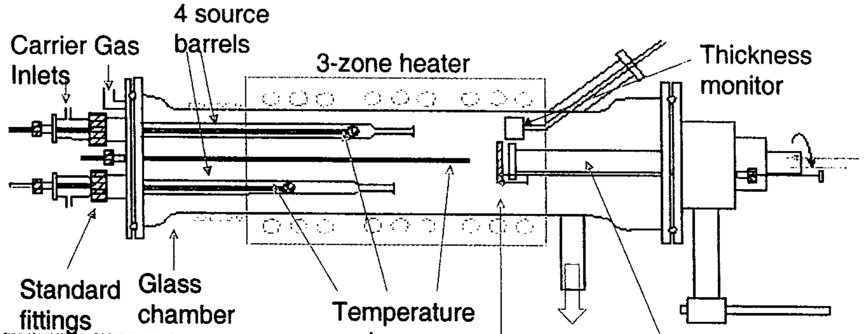
Organic Vapor Phase Deposition

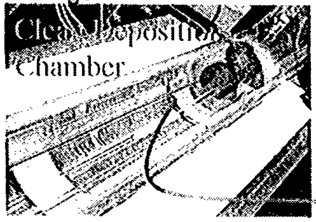
Chamber pressure: 0.1-10 Torr



- Controlled and accurate doping
- Dust free chamber
- Efficient materials use
- Control of film crystal structure

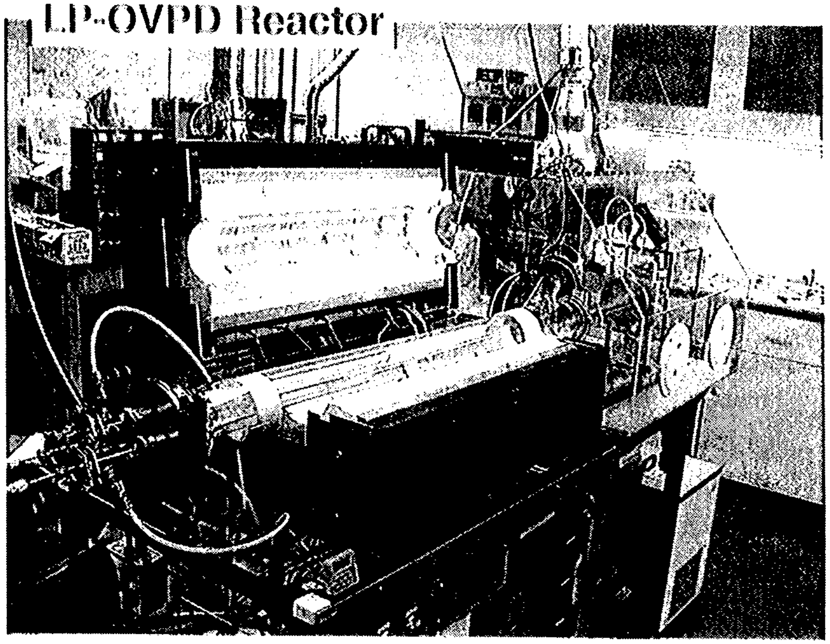
OVPD: Deposition System Design





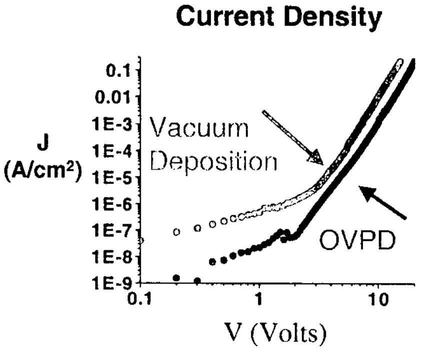
Isothermally heated source ⇒
Efficient & Controlled Evaporation:
0.3 grams of material last > 150 films

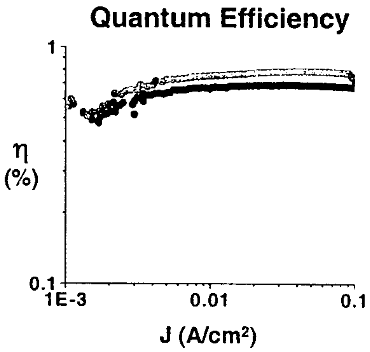
LP-OVPD Reactor



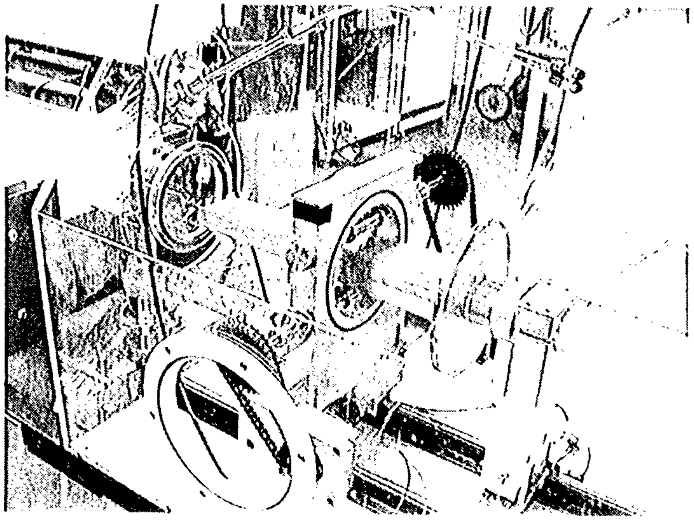
OVPD vs. Vacuum Deposition: OLEDs

MgAg	1000 Å
Alq_3	500 Å
α-NPD	500 Å
ITO	1000 Å
Glass/Plastic	1 mm


Current Density

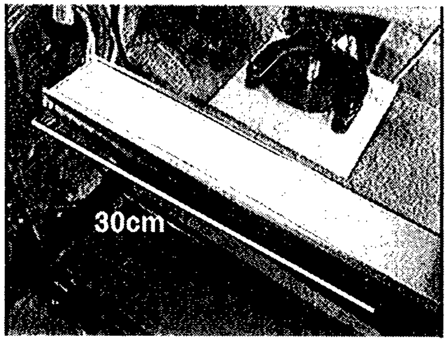

Quantum Efficiency

OVPD for Roll-to-Roll Deposition:

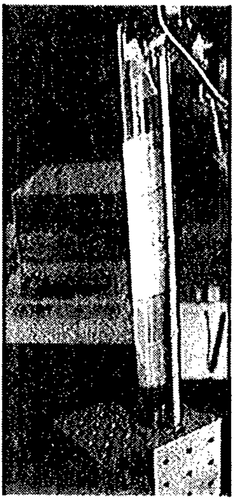


OVPD for Roll-to-Roll Deposition of OLEDs:

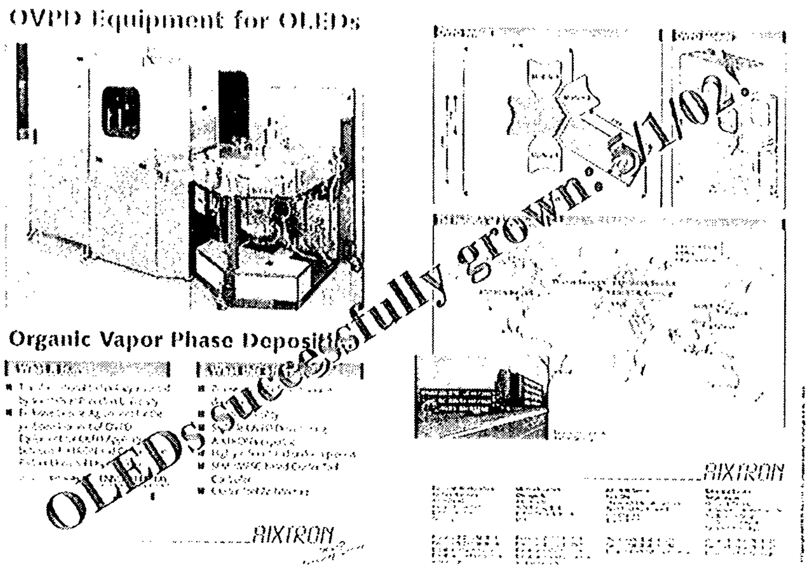
1st demonstrated OLED heterostructure and working device on >30 cm plastic ribbon



30x5cm, TPD/Alq_3 plastic ribbon substrate



100x5cm, **TPD**/DCM2-Alq_3 plastic ribbon substrate



OVPD Equipment for OLEDs

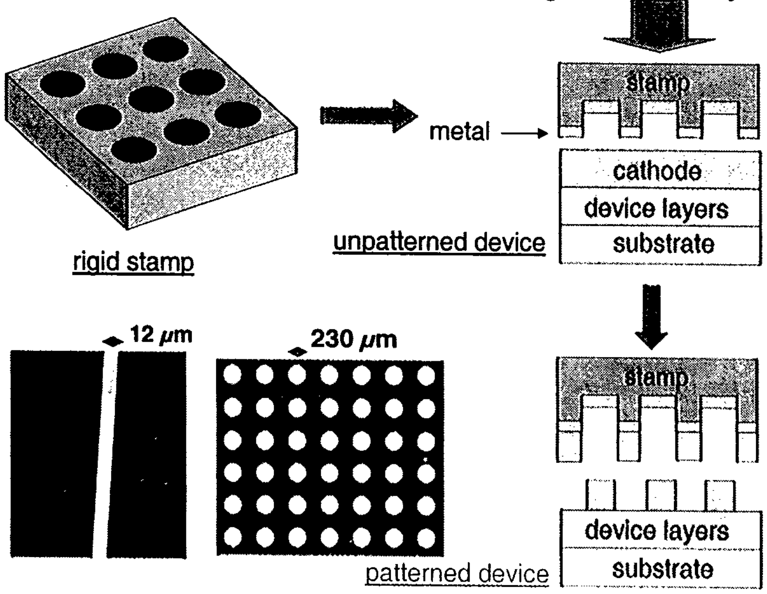
Organic Vapor Phase Deposition

AIXTRON

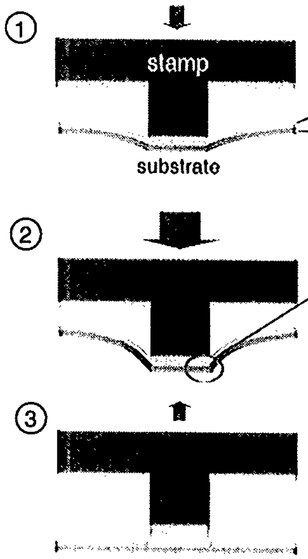
AIXTRON

OLEDs successfully grown: 5/1/02

Direct nanopatterning by cold-welding followed by lift-off



mechanism



cold-welding occurs

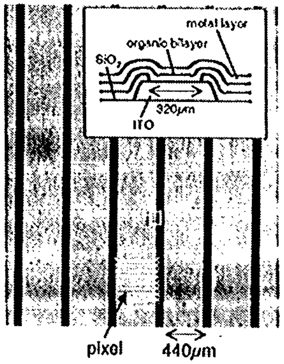
Highly concentrated normal stress

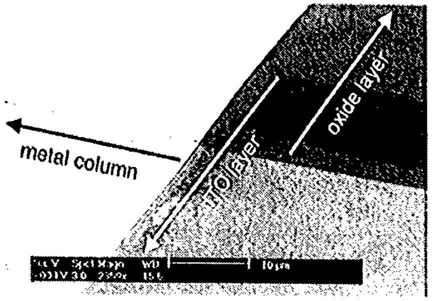
↓

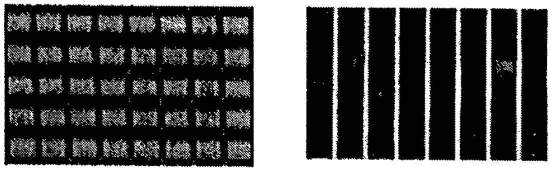
weaken the boundaries

fracture along the
boundaries upon
separation of the stamp
from the substrate

Display Fabrication Using Cold-Welding Followed by Lift-Off

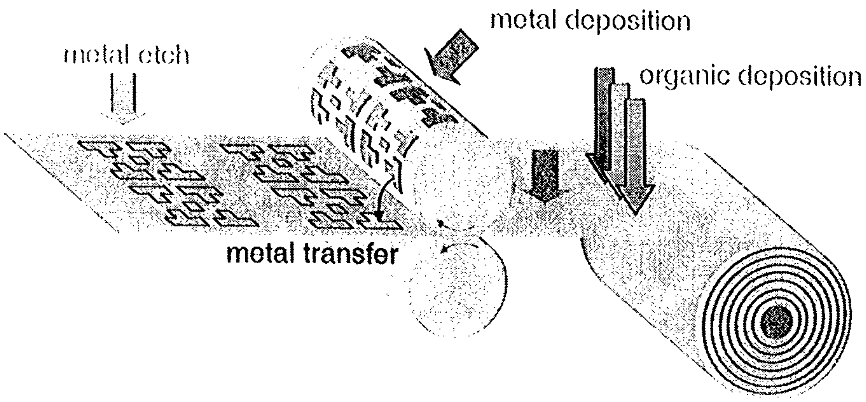






Passive-Matrix OLED Display in Operation

OVPD & Cold-Welding:
web-processing of organic devices



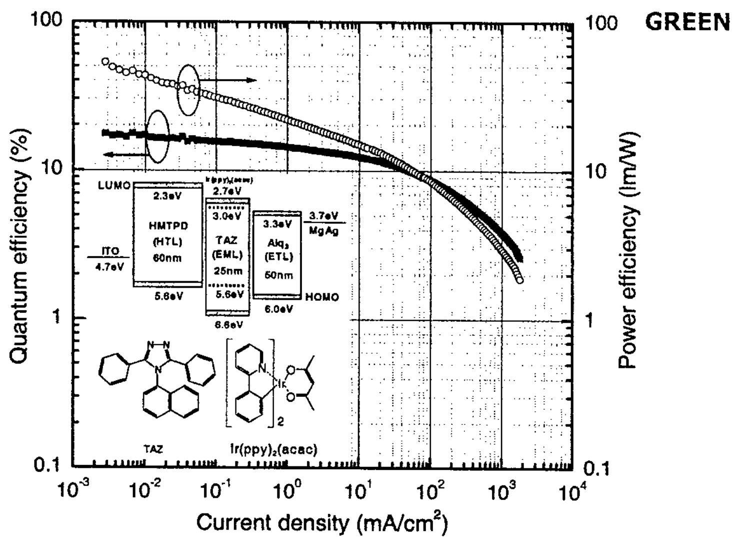
Recent advances in small molecular weight displays

Stephen Forrest
Department of Electrical Engineering
Princeton University

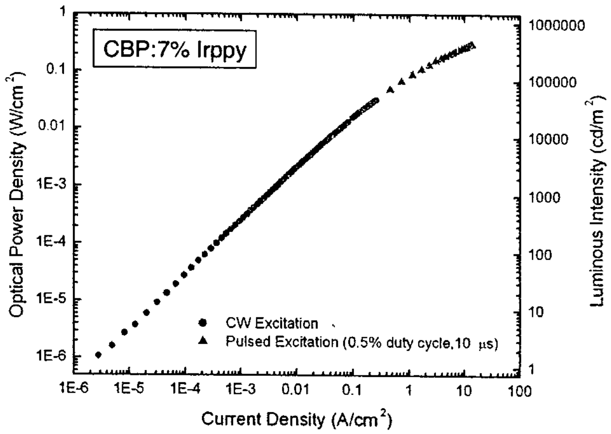
Accomplishments

- Achieved high brightness greens and deep blues
- Demonstrated efficient phosphor polymer devices
- Demonstrated efficient, simplified white OLEDs
- Modeled and demonstrated high resolution patterning by OVPD
- Developed "unified model" of current-voltage characteristics of OLEDs
- Demonstrated cold-welding by metal addition

Ir(ppy)$_2$(acac) doped ETL (Triazole) (η_{ext}=19%, η_{int}=87%)



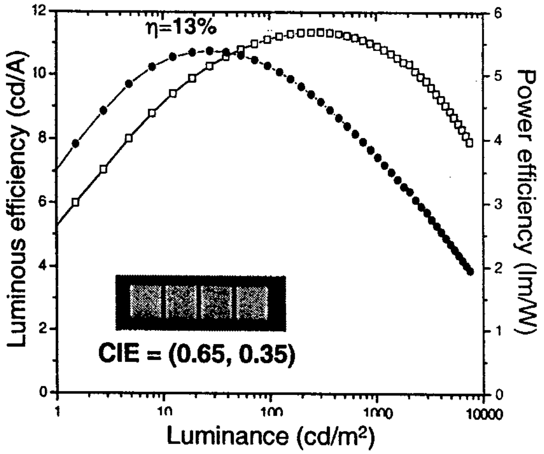
High Brightness Phosphorescent Devices



Peak brightness of a 13% efficient CBP:7% Irppy device approaches 5×10^5 cd/m^2 and 0.3 W/cm^2

Compare to a 1.7% efficient **CBP** device with 6×10^4 cd/m^2 and an optical power density of 0.2 W/cm^2 under the same excitation

Red PHOLED Performance



CIE = (0.65, 0.35)

cd/m^2	cd/A	V
100	11.2	6.8
300	11.4	7.8
500	11.3	8.3

UNIVERSAL DISPLAY
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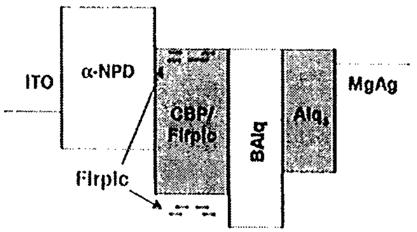
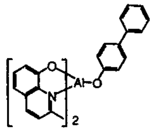
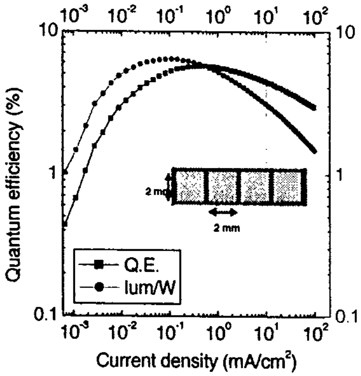
Blue Electrophosphorescence from FIrpic/CBP





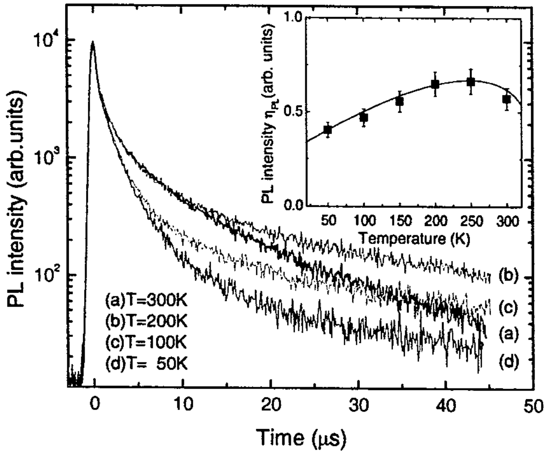
BAlq



- Emission due solely to phosphorescent dopant
- FIrpic carries electrons in CBP
- Efficiency = 5.5%, > 5 lum/W, 12 cd/A at 100 cd/m²

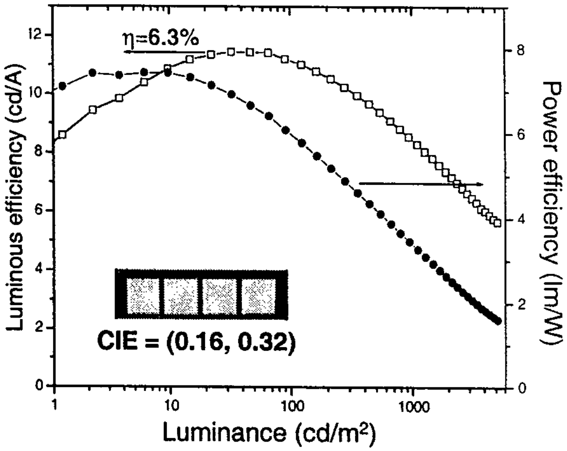
[illegible] University

Temperature Dependent PL of FIr(pic)



Princeton University

Blue PHOLED Performance

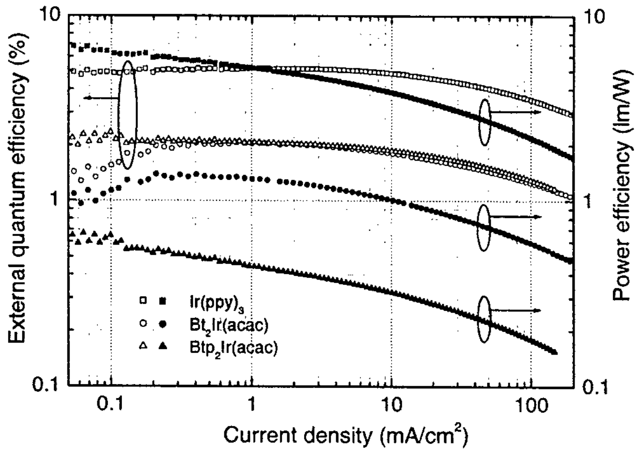


CIE = (0.16, 0.32)

cd/m^2	cd/A	V
100	11.1	5.8
500	9.6	7.2
1000	8.5	8.3

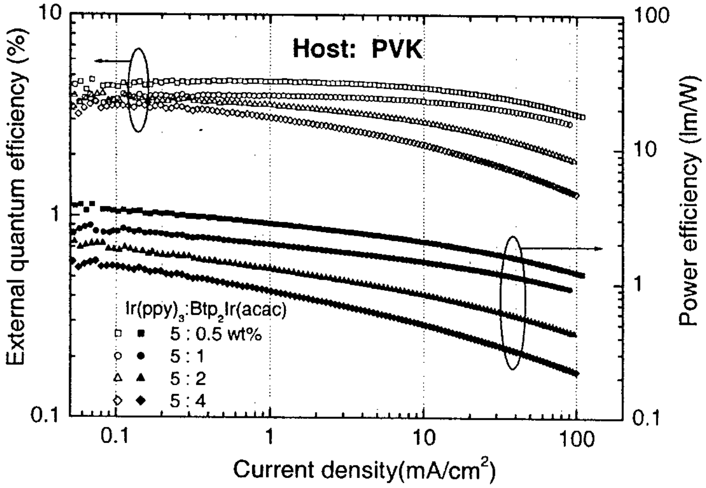
UNIVERSAL DISPLAY
CORPORATION™

Polymer based Electrophosphorescence



Efficiencies considerably less than small molecules:
Due to low lying triplet and defect states in PVK host defeating energy transfer

2.5 times enhancement of red efficiency by phosphor sensitization

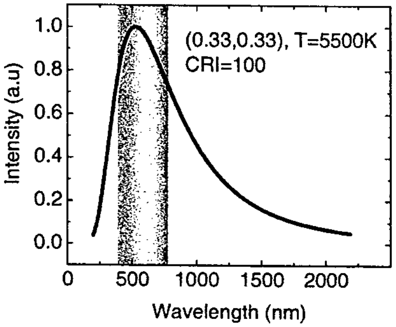


Summary of Efficiencies in EP-OLEDs

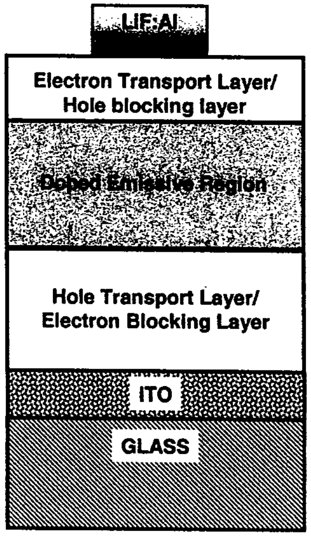
			$J = 1\ \mu A/cm^2$				$J = 1\ mA/cm^2$			
phosphor	**host**	Φ (lm/W)	η_P (lm/W)	$\eta_{Q\,ext}$	$\eta_{Q\,int}$	V_λ/V	η_P (lm/W)	$\eta_{Q\,ext}$	$\eta_{Q\,int}$	V_λ/V
ppy$_2$Ir(acac)	TAZ	530	60	0.19	0.87	0.60	20	0.15	0.68	0.25
btpIr(acac)	CBP	170	4	0.07	0.32	0.34	2.2	0.06	0.27	0.22
FIrpic	CBP	260	1.3	0.006	0.027	0.83	5.0	0.057	0.23	0.34
PtOEP	CBP	60	0.3	0.056	0.23	0.09	0.2	0.042	0.19	0.08

Organic White Light Emitters

- Use several dopants to achieve high efficiency via energy transfer to radiative triplet states
- Mix several dopants to attain
  - ✓ CIE chromaticity coordinates of (0.33,0.33)
  - ✓ High color rendering index Scale of 0-100



Structure of doped OLED


LiF:Al

Electron Transport Layer/ Hole blocking layer

Doped Emissive Region

Hole Transport Layer/ Electron Blocking Layer

ITO

GLASS

Challenges for white:-

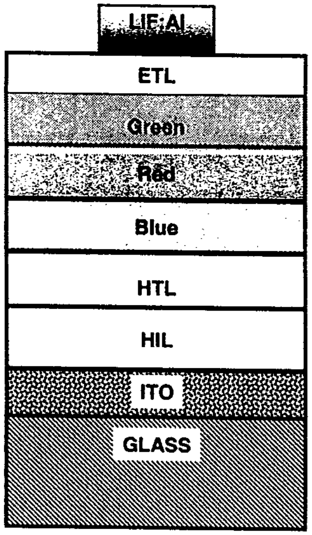
- Avoid cascade of energy from blue and green emitters to red emitter
- Tuning device color

Separating dopants into bands

- Prevent energy transfer between dopants.
- Control relative emission intensity of dopants by:
  - ✓ Varying doping concentrations (>1wt%) using thermal evaporation
  - ✓ Adjusting the thickness of bands
  - ✓ Inserting blocking layers
  - ✓ Adjusting the position of the dopants relative to the HTL

Why does it work?

- Triplets can diffuse much further than singlets (measured ~1000Å)
- Good control over diffusion of excitons using blocking layers and layer thickness


LiF:Al

ETL

Green

Red

Blue

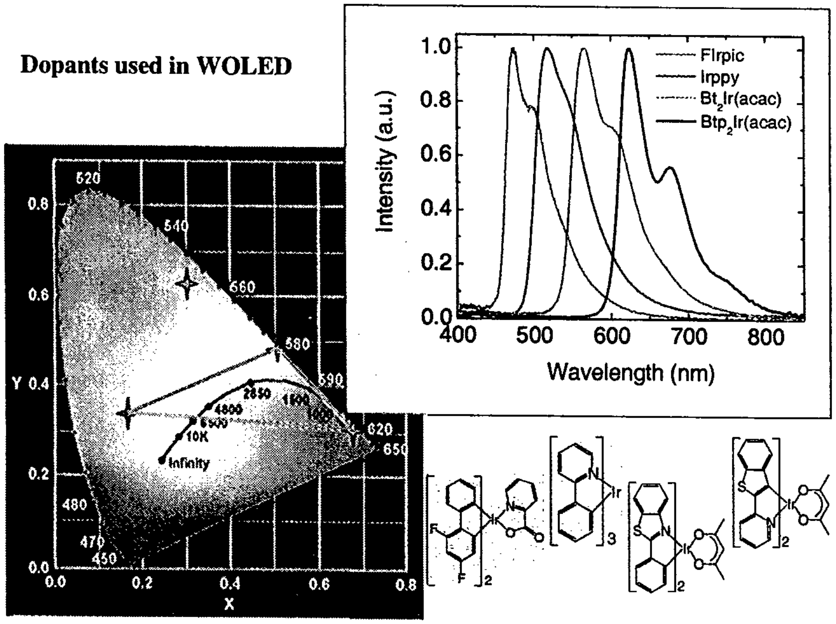
HTL

HIL

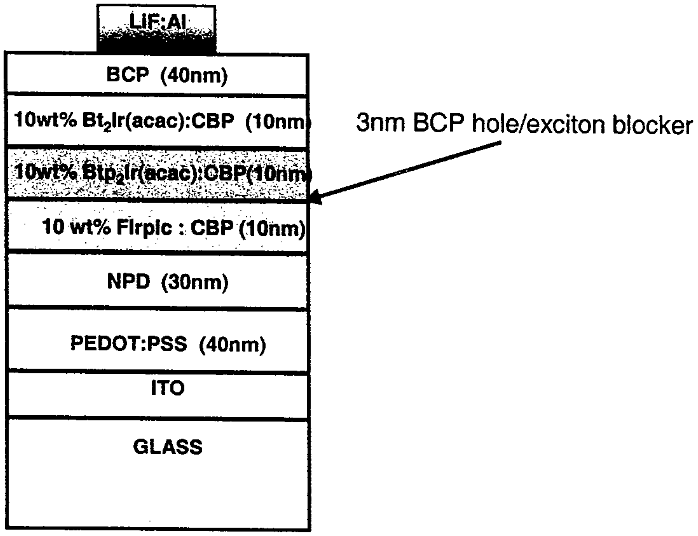
ITO

GLASS

Dopants used in WOLED



Efficient, Color Balanced White Light Emitter


LiF:Al

BCP (40nm)

10wt% $Bt_2Ir(acac)$:CBP (10nm

10wt% $Btp_2Ir(acac)$:CBP(10nm

10 wt% FIrpic : CBP (10nm)

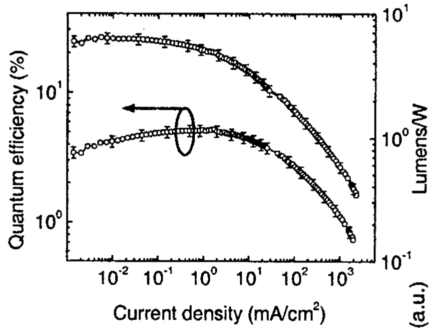
NPD (30nm)

PEDOT:PSS (40nm)

ITO

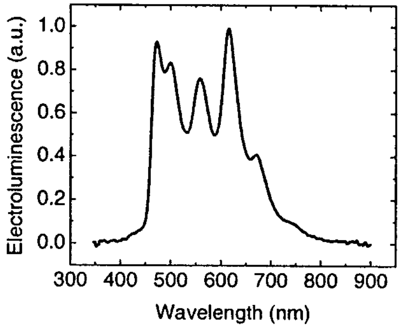
GLASS

3nm BCP hole/exciton blocker



CIE = (0.37, 0.40), CRI = 83

- Max luminance 31,000 cd/m² at 14V
- η_{ext} = 5.2 %, η_p = 6.4 lm/W



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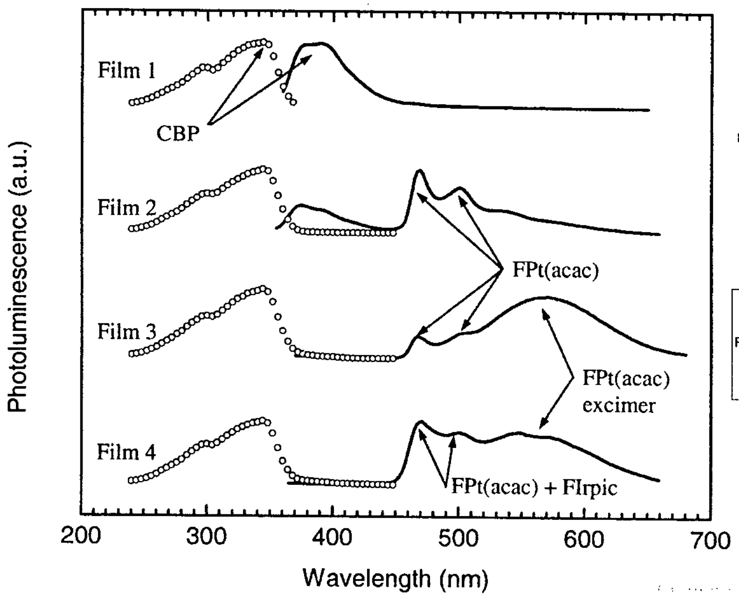
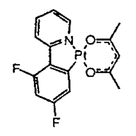
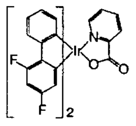
Broad Excimer Emission Simplifies Device Structure



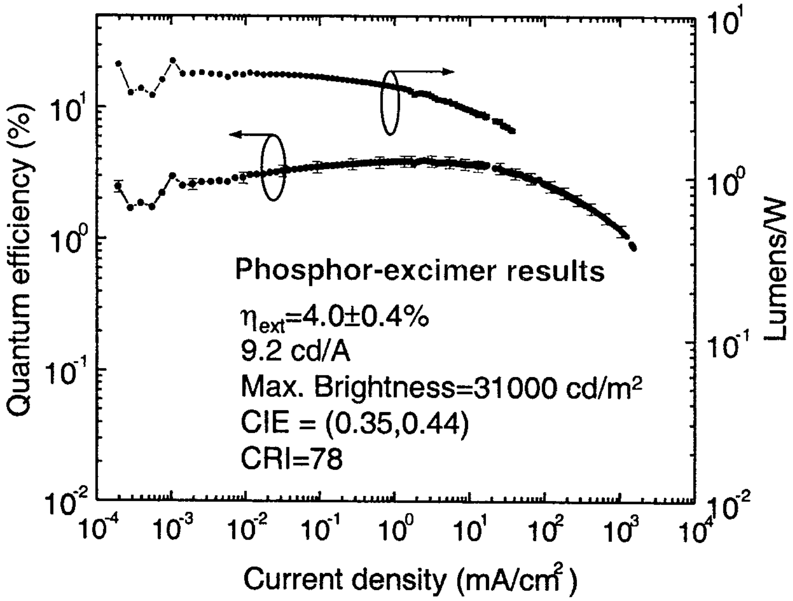


FPt(acac)



FIrpic

Princeton University

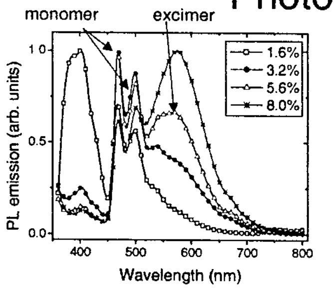


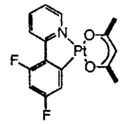
Phosphor-excimer results

η_{ext}=4.0±0.4%
9.2 cd/A
Max. Brightness=31000 cd/m²
CIE = (0.35,0.44)
CRI=78

Princeton University

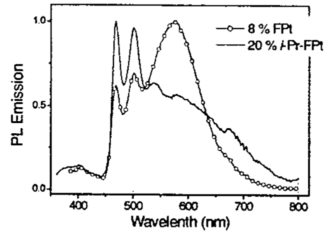
Single Dopant Monomer – Excimer Photoluminescnce

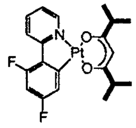




in CBP

- monomer dopant emission at low doping level
- balanced monomer/excimer ~5%
- CBP fluorescence at low doping levels
- Increasing steric bulk hinders excimer formation
  - can it lead to greater monomer:excimer ratio?





in CBP

- replacing methyl groups with *i*-Pr adds significant steric bulk
- Only weak excimer emission observed at doping levels as high as 20%
- too much steric bulk gives only monomer⇒ intermediate steric bulk.

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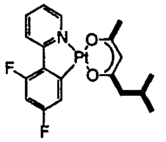
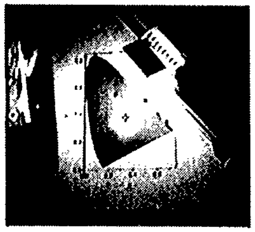
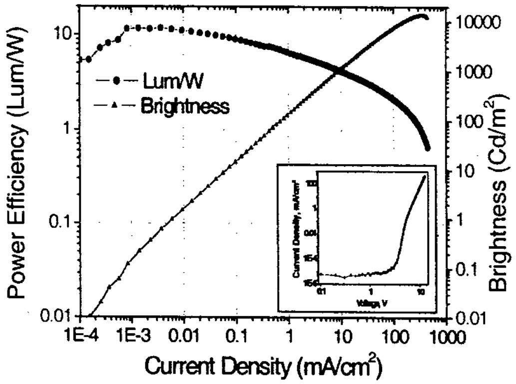
High Efficiency Single Dopant WOLEDs



doped luminescent layer

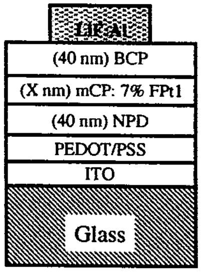
CIE: 0.39 0.41
CRI: 76



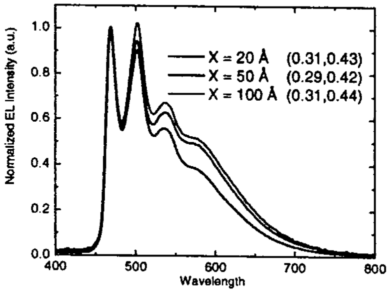


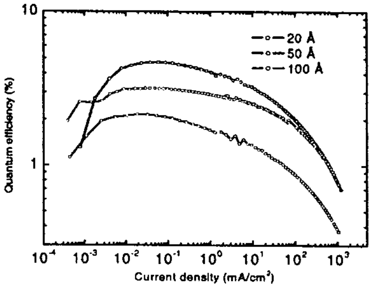
- Q.E = 5.8% , 9 lm/W @ 50 cd/m^2
- Q.E.= 4.5% , 5.1 lm/W @ 500 cd/m^2

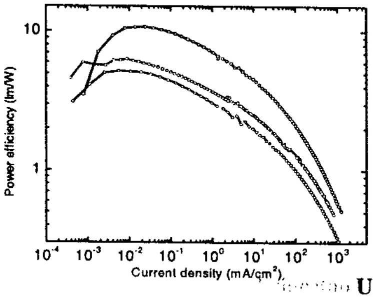
White electroluminescence spectra, J-V and luminance



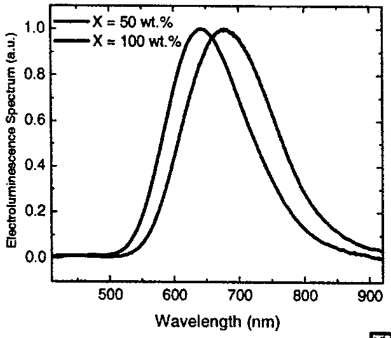
LiF/Al
(40 nm) BCP
(X nm) mCP: 7% FPt1
(40 nm) NPD
PEDOT/PSS
ITO
Glass

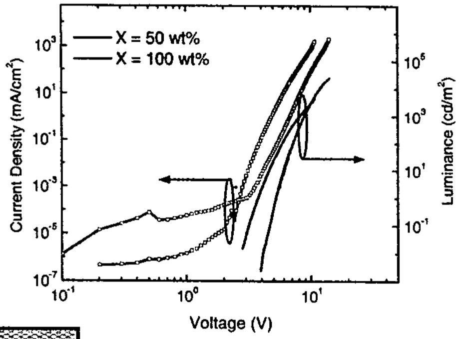


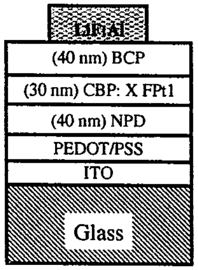




Red electroluminescence spectra, J-V and luminance

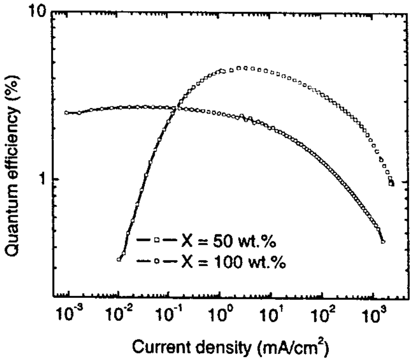


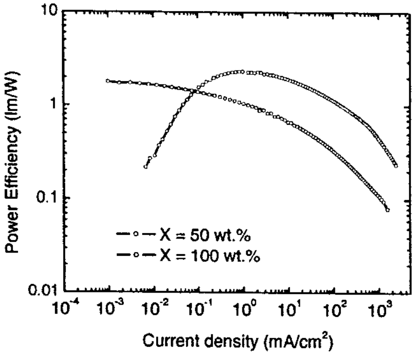




LiF/Al
(40 nm) BCP
(30 nm) CBP: X FPt1
(40 nm) NPD
PEDOT/PSS
ITO
Glass

Red external power and quantum efficiencies



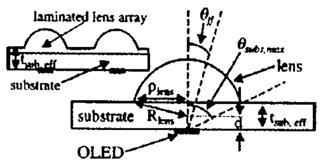


Optical elements

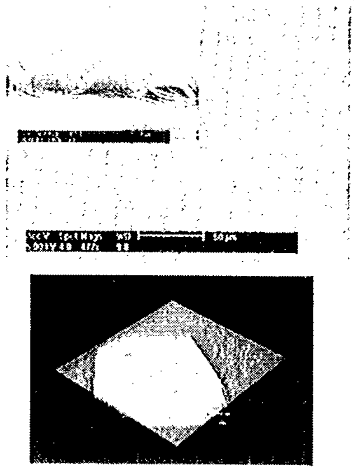
Low index substrates

T. Tsutsui, M. Yahiro, H. Yokogawa, K. Kawano, and M. Yokoyama, Adv. Mater. **13**, 1149 (**2001**).

Lenses

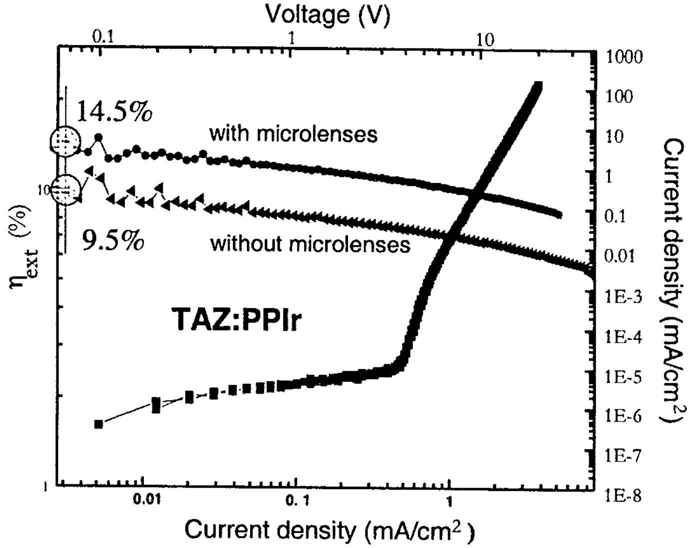


V. Bulovic, V. B. Khalfin, G. Gu, P. E. Burrows, D. Z. Garbuzov, and S. R. Forrest, Phys. Rev. B **58,** 3730 (**1998**).
Picture: C. F. Madigan, M. H. Lu, and J. C. Sturm, Appl. Phys. Lett. **76,** 1650 (**2000**).

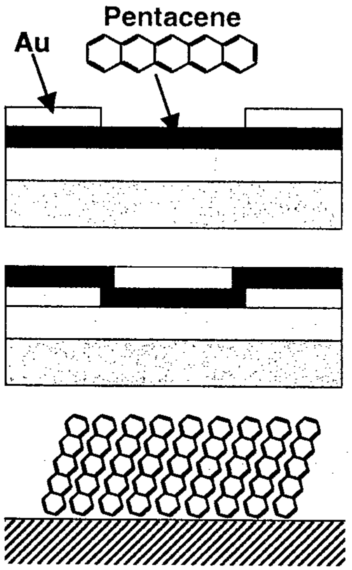


S. Möller and S. R. Forrest. MRS Fall Mtg., (**2001**), Paper BB6.9

External Quantum Efficiency



Thin Film Transistors with Pentacene Channels



"Top-contact"

Long (>10μm) channels
Shadow Masking /
Cold-Welding

"Bottom-contact"

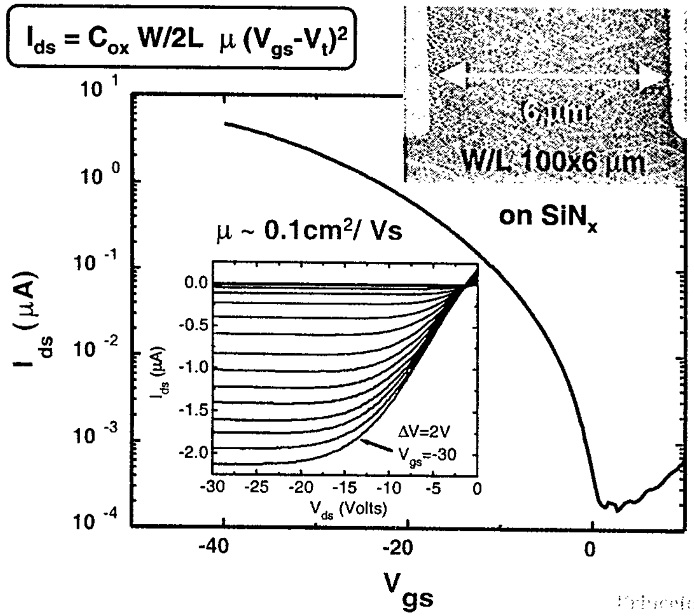
Shorter channels
Photolithography

Charge Transport

Along π overlap
Trap-limited

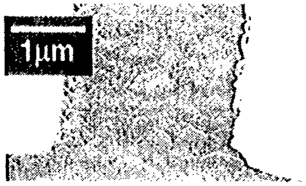
Pentacene TFTs by OVPD, *Bottom Contact*

$$I_{ds} = C_{ox}\, W/2L\ \ \mu\, (V_{gs}-V_t)^2$$



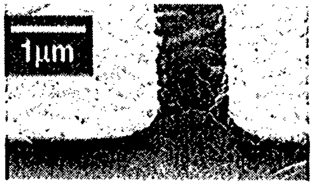
Reaching Single-Crystal mobility with *BC* geometry

a. reduce channel length → **"fails"**
b. increase grain size



0.8 Torr
10°C
grain < 1μm
L = 2μm
-> μ = 0.1

Bottom contact



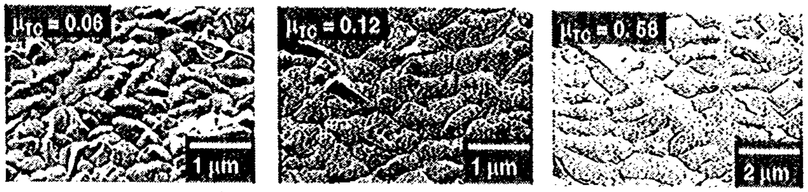
8 Torr
65°C
grain > 1μm
L < 1μm
-> μ = 0.01

OTS-treated SiO_2
μ ≈ 2 cm^2/Vs
* Jackson et al.

Bottom contact

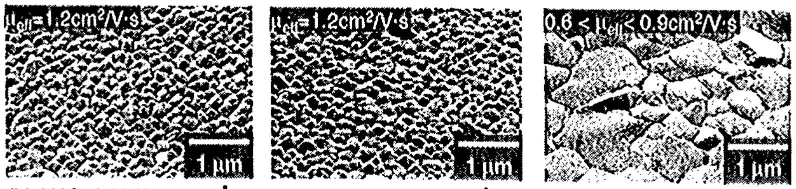
Controlling Pentacene Film Morphology - *Top Contact Geometry*

Pentacene on SiO_2



(a) 10°C, 0.25 Torr, 3.0 Å/s (c) 40°C, 6.0 Torr, 1.0 Å/s (e) 65°C, 10.5 Torr, 0.3 Å/s

Pentacene on OTS-treated SiO_2



(b) 10°C, 0.25 Torr, 3.0 Å/s (d) 40°C, 6.0 Torr, 1.0 Å/s (f) 65°C, 10.5 Torr, 0.3 Å/s

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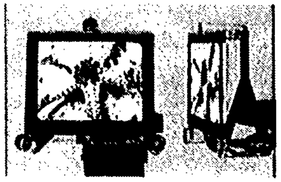
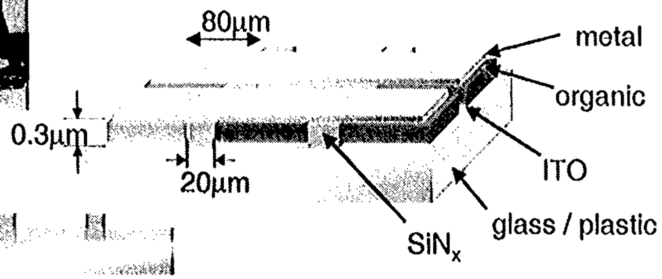
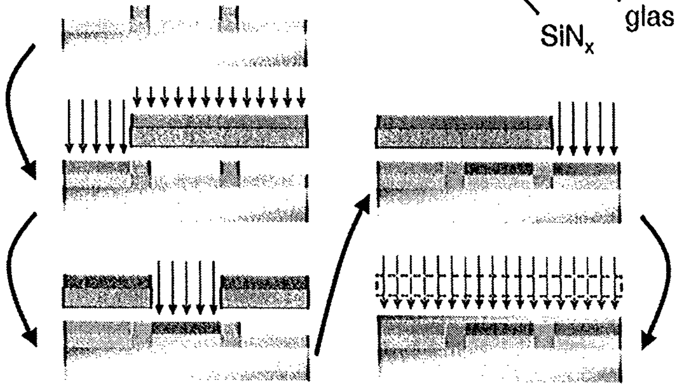


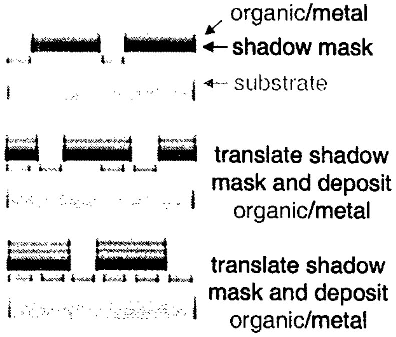
OLED Structure





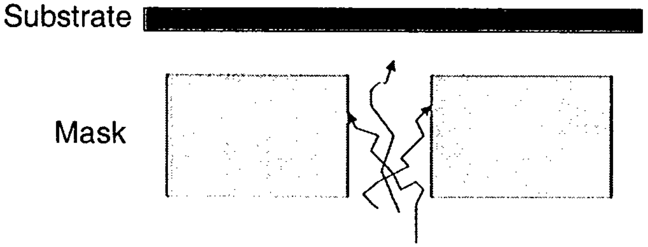
Patterning of Full Color Displays

- Conventional shadow mask technique



Limitations:
- Resolution determined by mask thickness
- Requires integrated shadow mask (ISM)
- Requires precise positioning

Growth through apertures

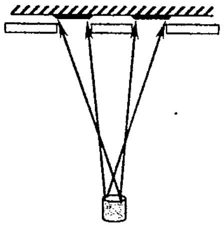


- Will surface absorption prevent deposition at the substrate?
- What pattern resolution is achievable?

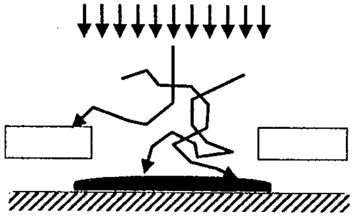
Patterned deposition through masks necessary for full color displays and other applications

Micropatterning of organic thin films: experiment

Mask thickness = 7μm **Mask separation 3μm**
Aperture = 7.5 μm **Carrier velocity 1 m/s**

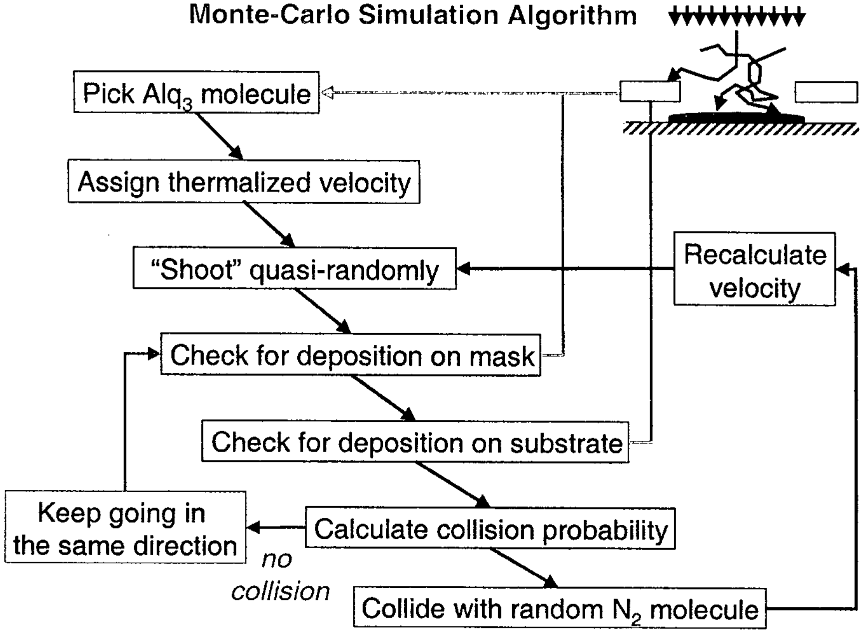


Evaporation at 10^{-6}Torr



OVPD at 0.1 Torr

Monte-Carlo Simulation Algorithm



Pick Alq_3 molecule

Assign thermalized velocity

"Shoot" quasi-randomly

Check for deposition on mask

Check for deposition on substrate

Calculate collision probability

Keep going in the same direction

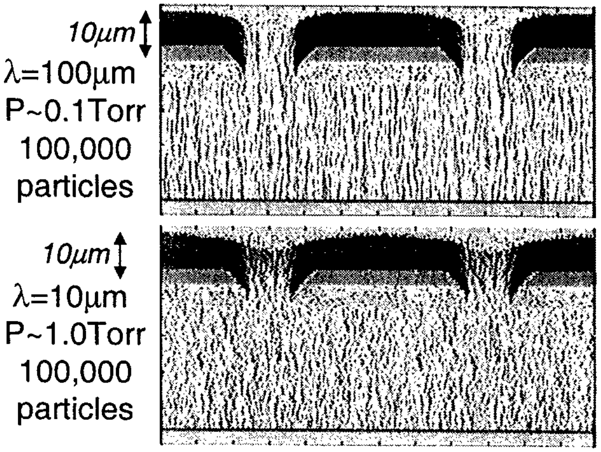
no collision

Collide with random N_2 molecule

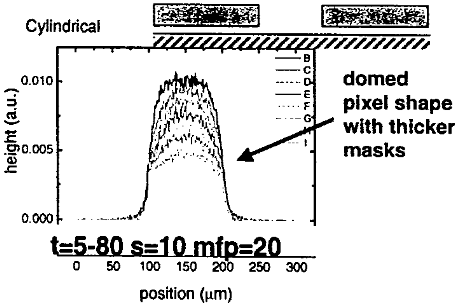
Recalculate velocity

Alq_3 film deposition in N_2 background

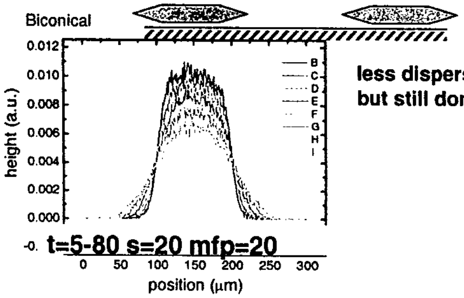
pattern evolution in time



Effect of masking geometry on pixel shape

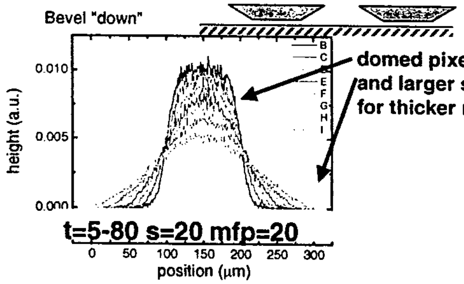


domed pixel shape with thicker masks

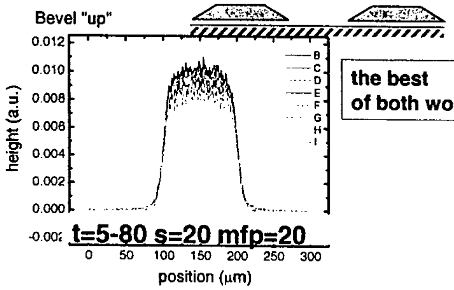


less dispersion, but still domed

Effect of masking geometry on pixel shape



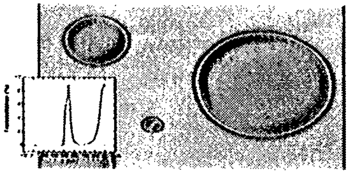
domed pixels and larger spread for thicker masks



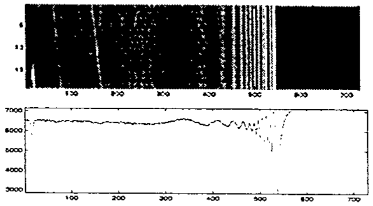
the best of both worlds...

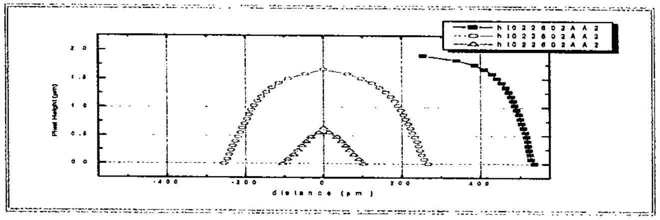
Experimental determination of pixel shape

1. Microscope w/ monochromatic light source

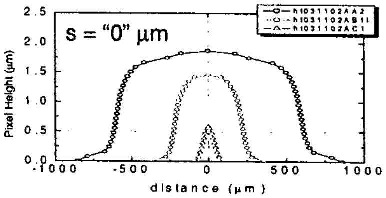


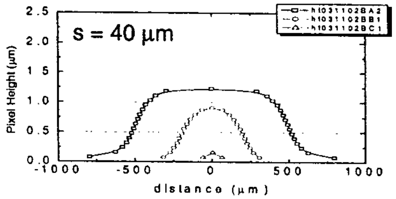
2. Digitize image and count fringes

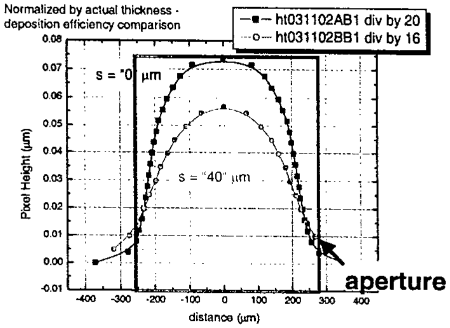




Example: cylindrical aperture, 0.16 Torr
vary pixel size, vary separation

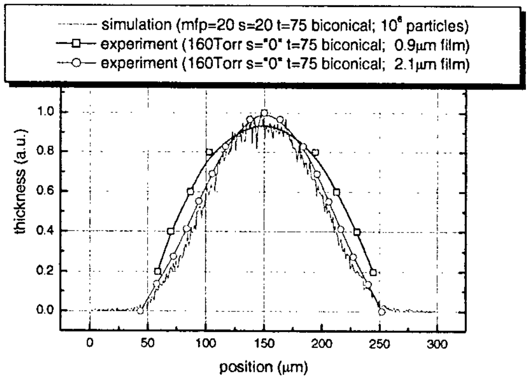






Smaller patterns & comparison w/ simulation

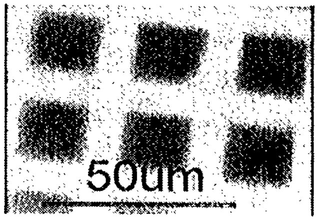
Biconical Mask, 100μm aperture

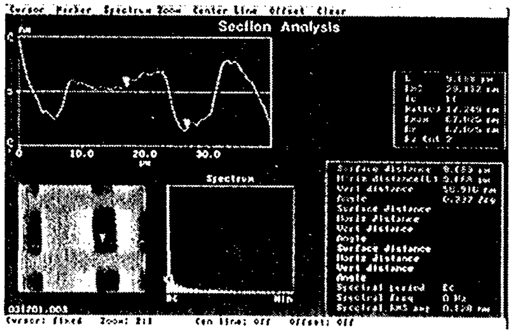


University

Really small patterns → AFM

@ 1.4Torr

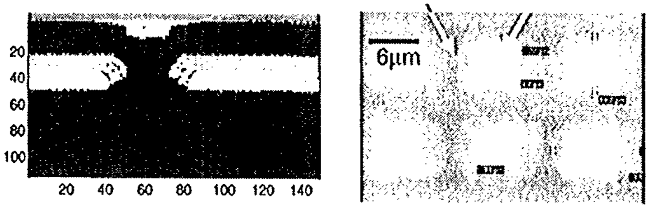




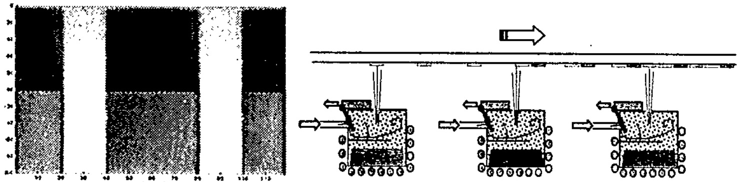
University

Hybrid OVPD + vacuum Deposition

λ=5μm OVPD @ 1 Torr VTE @ 10^{-6}Torr

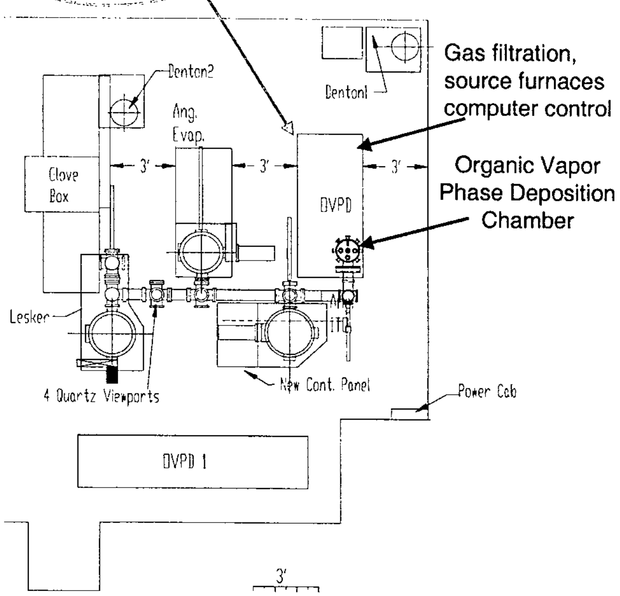


Organic vapor jet deposition: for home office?



University

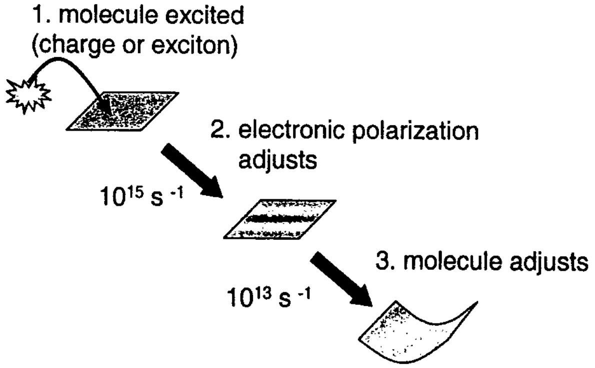
Full lab layout with new OVPD system



University

INTRODUCTION TO ELECTRON TRANSFER

Incoherent energy transfer



1. molecule excited (charge or exciton)

2. electronic polarization adjusts

10^{15} s^{-1}

3. molecule adjusts

10^{13} s^{-1}

Born-Oppenheimer approximation:
electronic motion is much faster than nuclear motion.

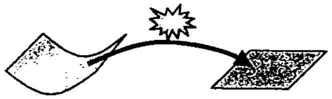
> Rate of energy and charge transfer is limited by nuclear motion, and the reconfiguration of the molecules

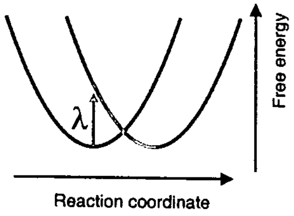
---

Marcus electron transfer

Represent molecules as simple harmonic oscillators.
Intermolecular overlap energy is small ~10 meV.

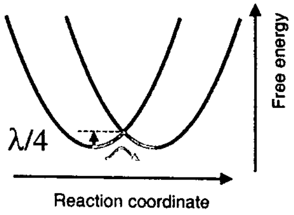
Both molecules in relaxed state:





Reorganizational energy required = λ

If both molecules adjust:



Reorganizational energy required = λ/4

Typically, λ ~ 0.1 - 0.5 eV.

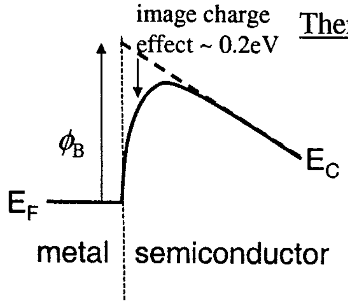
INJECTION LIMITED MODELS

> Thickness dependence of transport in Alq_3 is injection limited for thin films (d < 2000Å).

Traditionally semiconductor injection is analyzed following thermionic injection or tunneling injection.

Injection is strongly temperature dependent: eliminating tunneling injection.

Thermionic emission

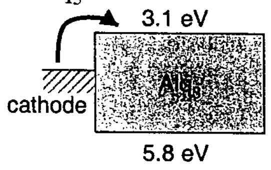


$$J = AT^2 \exp\left[-\left(\phi_B - \sqrt{qF/4\pi\varepsilon}\right)\Big/k_BT\right]$$

Richardson-Schottky Eqn.

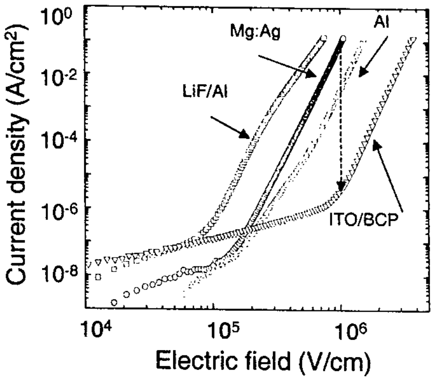
PROBLEMS WITH THERMIONIC EMISSION

Examine different cathodes on Alq_3.



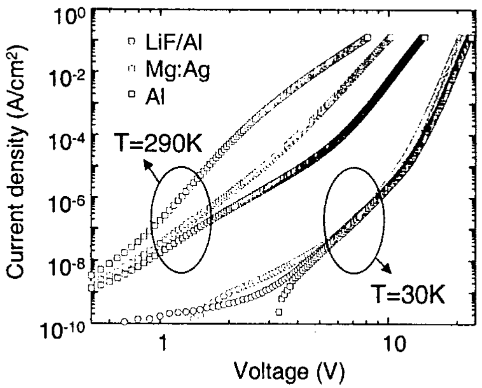
Work functions:
Mg: 3.7 eV
Al: 4.0 eV
Indium tin oxide (ITO): 4.7 eV

> From work function alone, we expect 1eV difference between Mg and ITO to reduce injection by factor of 10^{18}, actually only 10^5.



L.S. Hung et al. Appl. Phys. Lett. **70**, 152, 1997
G. Parthasarathy et al. Appl. Phys. Lett. **76**, 2128, 2000

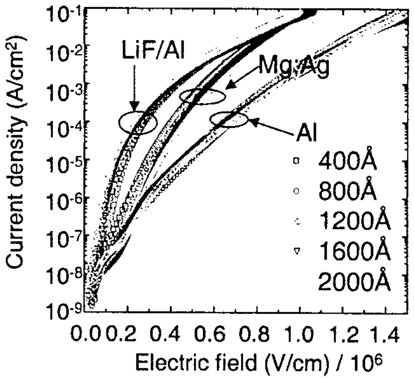
NO CATHODE DEPENDENCE AT LOW TEMPERATURES



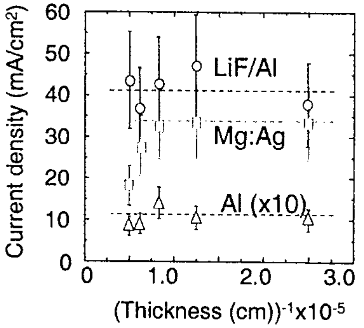
Transport is injection limited for T < 300K.

But transport is independent of cathode at low temperature - injection must depend on interfacial organic layers.

THICKNESS DEPENDENCE (II)



Thickness dependence at $F = 0.9\times10^6$ V/cm

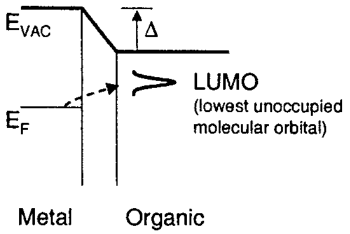


If transport is space charge limited (bulk limited), *J~1/d*, irrespective of field dependence of mobility.

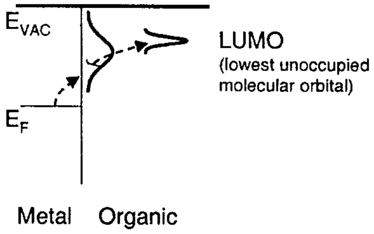
Characteristics are consistent with injection-limited transport.

THE METAL/ORGANIC INTERFACE

Reasons why the metal work function may not be an accurate measure of cathode injection efficiency.



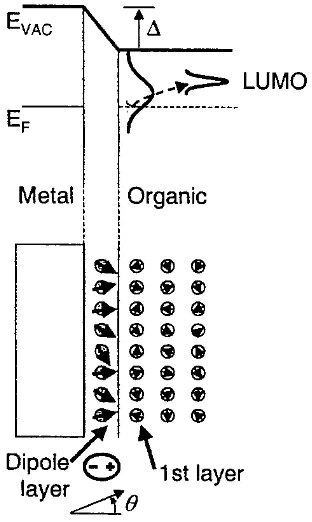
An interfacial dipole may shift the surface energy of the organic film



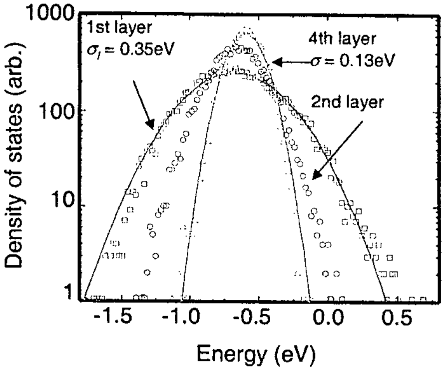
Intermediate states may reduce the overall hopping barrier

The presence of an interfacial dipole induces the intermediate states

DISORDER IN THE INTERFACIAL DIPOLE



Assuming interfacial dipoles of strength ~ 30D, and Gaussian orientation disorder with variance $\sigma = \pi$ radians, we get:



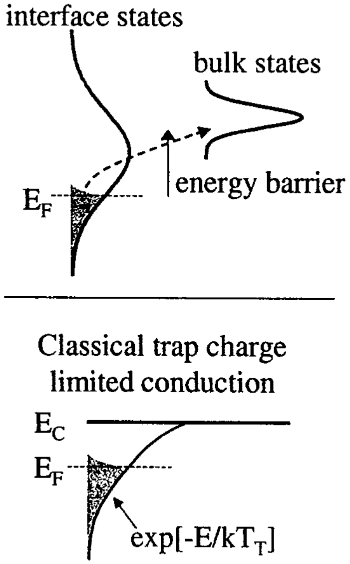
Alternately, disorder may be due to local variation in magnitude of dipoles

FEATURES OF THE INTERFACIAL STATE MODEL

- •Limiting step is hop from organic interface to organic bulk
- •Transport can be explained using only intrinsic properties

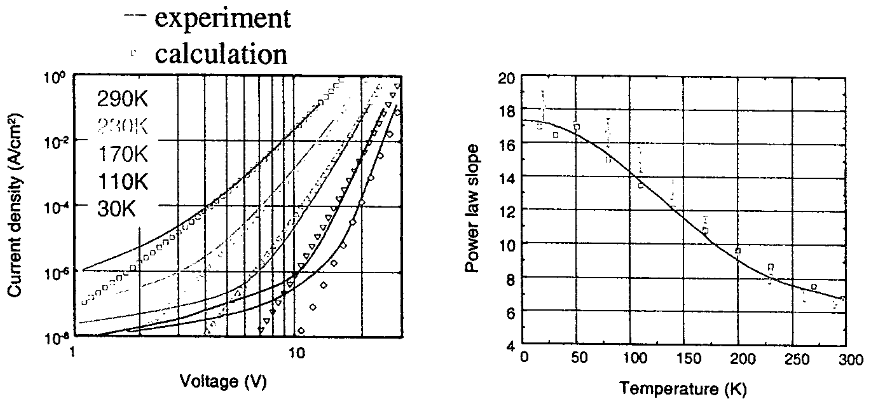
  No need for extrinsic effects such as traps.
- •Broad distribution of interface states generates power law transport

  -similar to trapped charge limited transport (distribution of states below a conduction level)



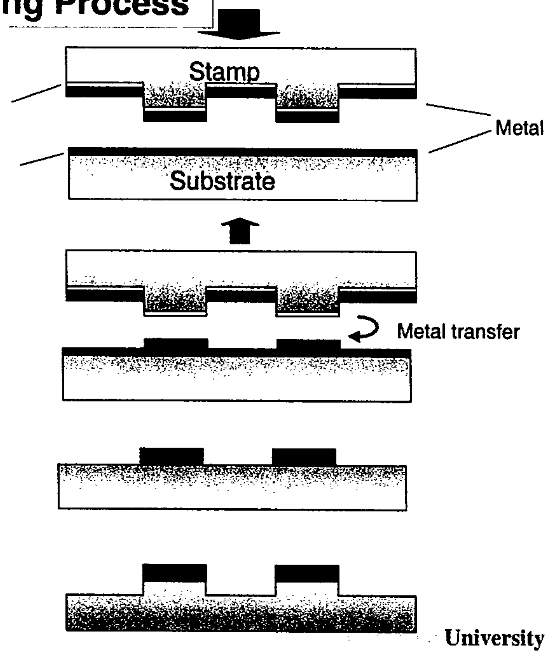
TEMPERATURE DEPENDENCE OF Mg:Ag/Alq$_3$ INTERFACE

Device: 300Å Ag / 1000Å 25:1 Mg:Ag / 1200Å Alq$_3$ / 1000Å Mg:Ag / SiN$_x$ / Si



Fit using polaron model for interfacial hop:
includes temperature dependence of phonon distribution

Additive Cold-welding Process



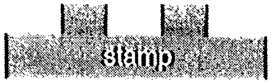
step 1

step 2
Cold welding

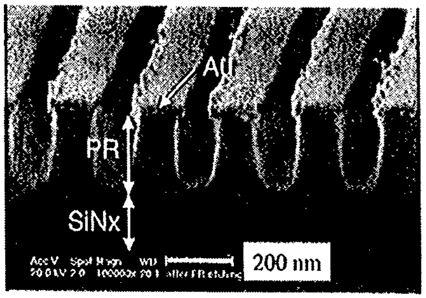
step 3
Strike layer removal

step 4
Pattern replication in a substrate

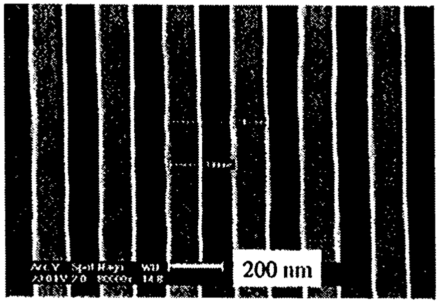
Cold-welding for high resolution lithography



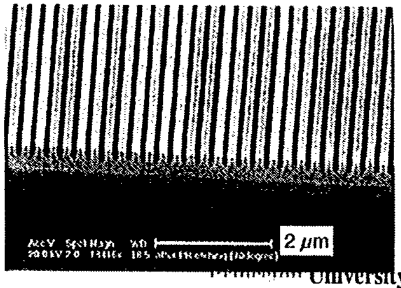
substrate: Si/SiNx/PR/
stamp: Si/Alq$_3$/
"parting layer"
200 MPa, 10 MPa/s, no hold time.
Au etch : Ar sputtering
PR etch : O$_2$ RIE



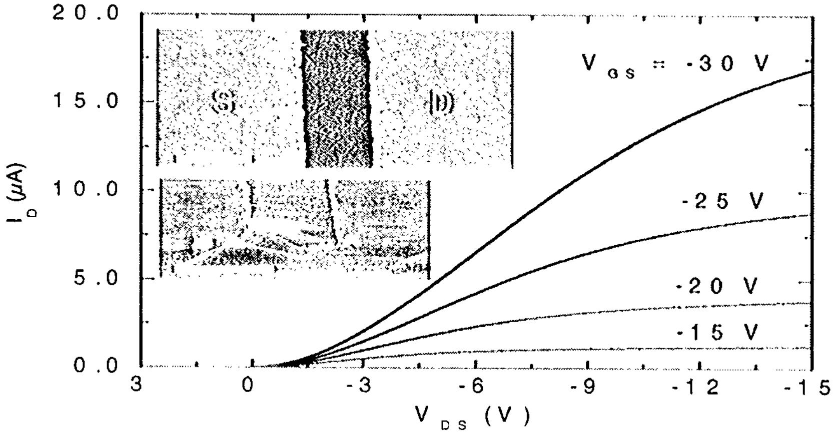
photoresist layer is etched



transferred metal lines



Additive Cold-welding for Narrow Gate OTFTs

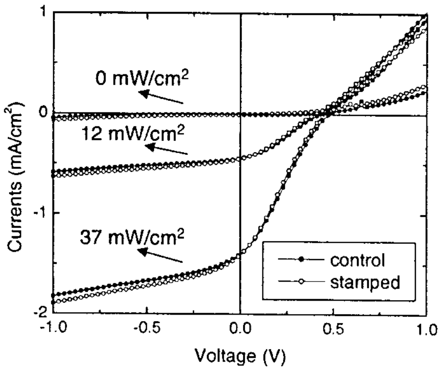


L=1 μm

μ~0.1 cm^2/V-s

University

Additive Cold-welding for Organic Solar Cells

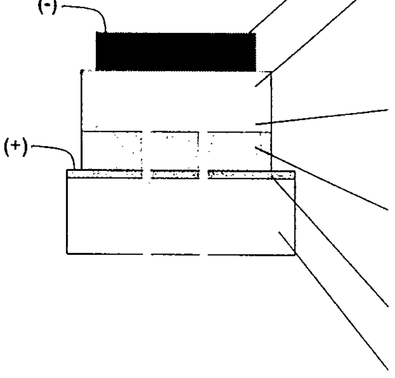


University

Advances in Chemistry of Materials for OLEDs

Mark Thompson
USC

Heterostructure OLEDs



Cathode: Mg, Ca, Al•LiF, ITO•Cupc

Electron transporting layer
- inorganic:Alq_3, Mq_n
- organic: oxidiazoles, triazoles
- polymer: cyano-PPV, polyfluorenes
- reductant (Li) doped Alq_3

Emissive Zone: can be different material from HTL/ETL
- doped or undoped?
- fluorescence vs. phosphorescence

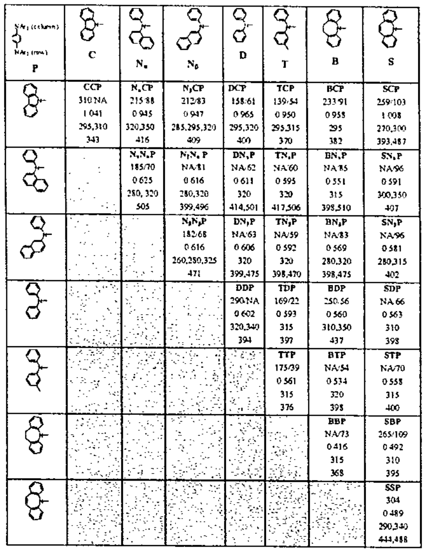
Hole transporting layer: NAr_3 (TPD, NPD, etc.)
- polymer: PVK, poly-TPD, PPV
- oxidant doped HTL ($FeCl_3$) - Kido

Anode: ITO, Sb or F doped SnO_2, TiN, metal

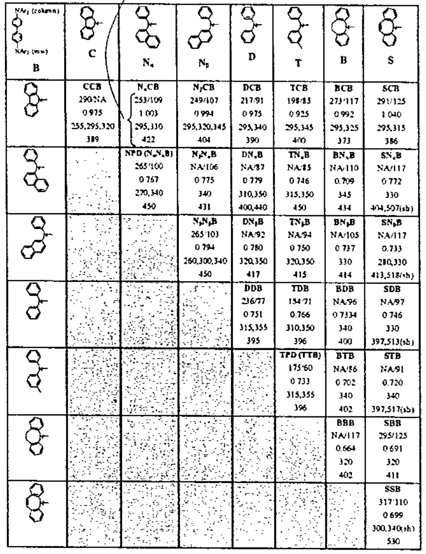
Substrate: glass, plastic, silicon, metal

Library of diamnes

T_g, T_m
E°_{ox}
PL (λ_{max})
abs (λmax)



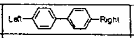
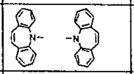
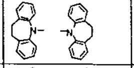
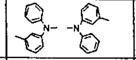
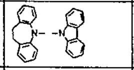
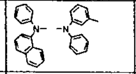
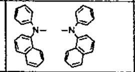
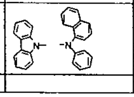
NAr_3 (column) NAr_3 (row) P	C	N_α	N_β	D	T	B	S
	CCP 310/NA 1.041 295,310 343	N_αCP 215/88 0.945 320,350 416	N_βCP 212/83 0.947 285,295,320 409	DCP 158/61 0.965 295,320 400	TCP 139/54 0.950 295,315 370	BCP 233/91 0.955 295 382	SCP 259/103 1.008 270,300 393,487
		$N_\alpha N_\alpha$P 185/70 0.625 280, 320 505	$N_\beta N_\alpha$ P NA/81 0.616 280,320 399,496	DN_αP NA/62 0.611 320 414,501	TN_αP NA/60 0.595 320 417,506	BN_αP NA/85 0.551 315 398,510	SN_αP NA/96 0.591 300,350 407
			$N_\beta N_\beta$P 182/68 0.616 260,280,325 471	DN_βP NA/63 0.606 320 399,475	TN_βP NA/59 0.592 320 398,470	BN_βP NA/83 0.569 280,320 398,475	SN_βP NA/96 0.581 280,315 402
				DDP 290/NA 0.602 320,340 394	TDP 169/22 0.593 315 397	BDP 250/56 0.560 310,350 437	SDP NA/66 0.563 310 398
					TTP 175/39 0.561 315 376	BTP NA/54 0.534 320 398	STP NA/70 0.558 315 400
						BBP NA/73 0.416 315 368	SBP 265/109 0.492 310 395
							SSP 304 0.489 290,340 444,488



NAr_3 (column) NAr_3 (row) B	C	N_α	N_β	D	T	B	S
	CCB 290/NA 0.975 255,295,320 389	N_αCB 253/109 1.003 295,330 422	N_βCB 249/107 0.994 295,320,345 404	DCB 217/91 0.975 295,340 390	TCB 198/85 0.925 295,345 400	BCB 273/117 0.992 295,325 373	SCB 291/125 1.040 295,315 386
		NPD ($N_\alpha N_\alpha$B) 265/100 0.767 270,340 450	$N_\beta N_\alpha$B NA/106 0.775 340 431	DN_αB NA/87 0.779 310,350 400,440	TN_αB NA/85 0.746 315,350 450	BN_αB NA/110 0.709 345 434	SN_αB NA/117 0.772 330 404,507(sh)
			$N_\beta N_\beta$B 265/103 0.794 260,300,340 450	DN_βB NA/92 0.780 320,350 417	TN_βB NA/94 0.750 320,350 415	BN_βB NA/105 0.737 330 414	SN_βB NA/117 0.733 280,330 413,518(sh)
				DDB 236/77 0.751 315,355 395	TDB 154/71 0.766 310,350 396	BDB NA/96 0.7334 340 400	SDB NA/97 0.746 330 397,513(sh)
					TPD (TTB) 175/60 0.733 315,355 396	BTB NA/56 0.702 340 402	STB NA/91 0.720 340 397,517(sh)
						BBB NA/117 0.664 320 402	SBB 295/125 0.691 320 411
							SSB 317/110 0.699 300,340(sh) 530

D. E. Loy, *et. al.*, *Chemistry of Materials*, **1998**, *10*, 2235-2250.

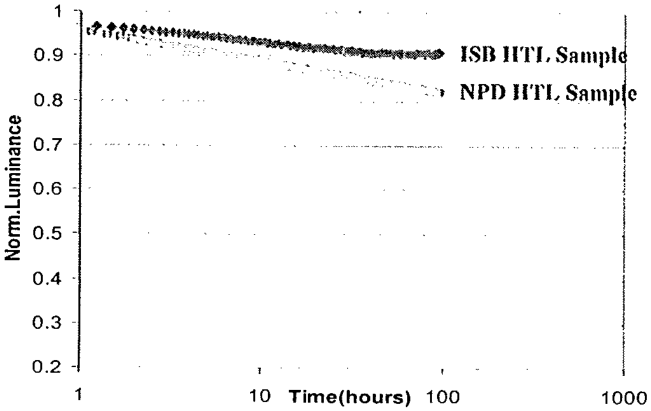
Diamine Hole Transporters in OLEDs

Compound		Tg (°C)	Potential relative to TPD, TPD = 0.775 V	η (%)	Voltage @ 0.1 mA
ISB		115	-0.044	0.65	9.6
IDB		110	-0.008	0.12	16
TPD (standard)		65	0	0.44	9.8
BCB		110	0.029	0.65	12.3
NTB		85	0.076	0.65	8.7
NPD (standard)		95	0.197	0.75	9.4
NCB		109	0.273	0.25	11.1
Alq_3		175	0.30		

- Device structure:
  ITO/HTL (400 Å)/Alq3 (400 Å)/Mg-Ag
- ISB has the best combination of efficiency and low voltage operation (similar to NPD), highest T_g
- D F. O'Brien, et. al., *Advanced Materials*, **1998**, *10*, 1108-1112.

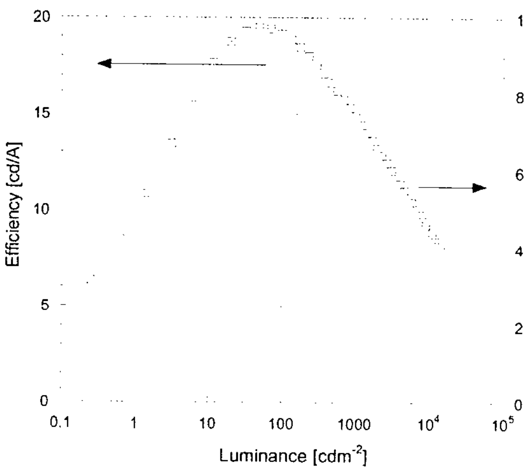
High T_g HTL Lifetime Comparison

$ITO/CuPc(100A)/HTL(500A)/CBP:PtOEP(300A)/Alq_3(200A)/MgAg$



UNIVERSAL DISPLAY CORPORATION

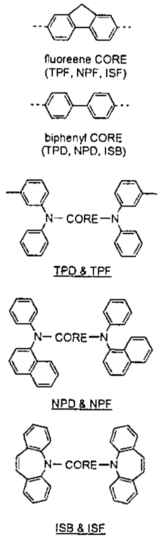
G1 structure with ISB as a HTL Efficiency vs. luminance



@600cdm^{-2}	ISB	NPD
Voltage [V]	7.2	7.6
Efficiency [cd/A]	18.6	21
Efficiency [Lm/W]	8.1	11

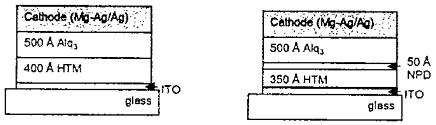
UNIVERSAL DISPLAY CORPORATION

Fluorene Cored HTLs



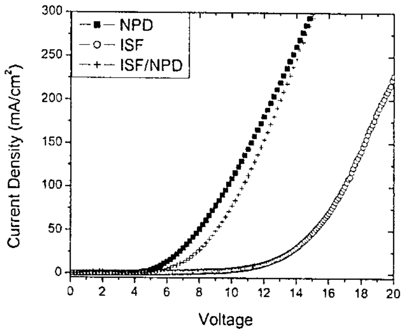
Material Acronym	TPF	TPD	NPF	NPD	ISF	ISB
Tg (°C)	78	60	118	95	161	115
1st Oxidation (vs. Ag/AgCl)*	0.626	0.733	0.658	0.767	0.516	0.699
Absorption/Emission (nm)	340/398	315, 355/396	360/470	270, 340/450	295/530	300/530

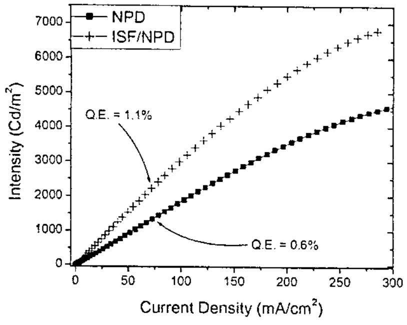
- Fluorene core gives higher T_g than biphenyl
- Lowers oxidation potential: raises HOMO energy
- What about OLEDs?



D. Loy, *et. al.*, *Adv. Func. Mat.*, **2002**, *12*, 245.

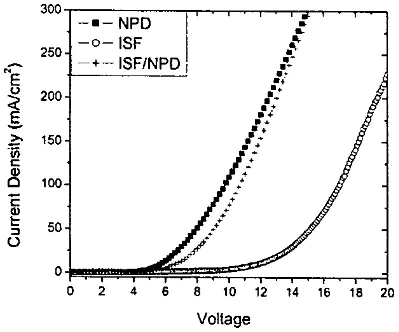
ISF based OLEDs

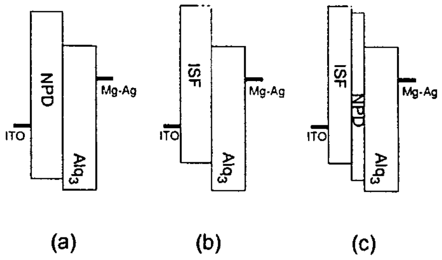




- NO LIGHT for ISF/Alq_3 device
- NPD interface layer is needed to efficiently inject holes from ISF to Alq_3
- ISF HOMO is too shallow

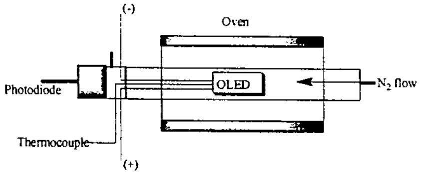
ISF based OLEDs

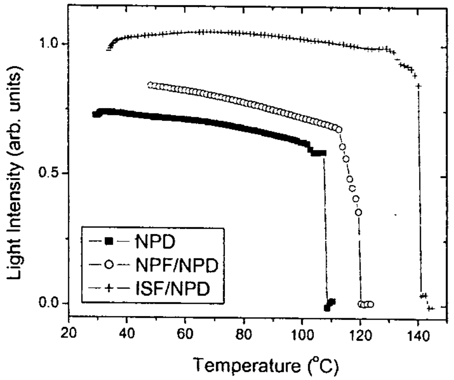




- NO LIGHT for ISF/Alq_3 device
- NPD interface layer is needed to efficiently inject holes from ISF to Alq_3
- ISF HOMO is too shallow

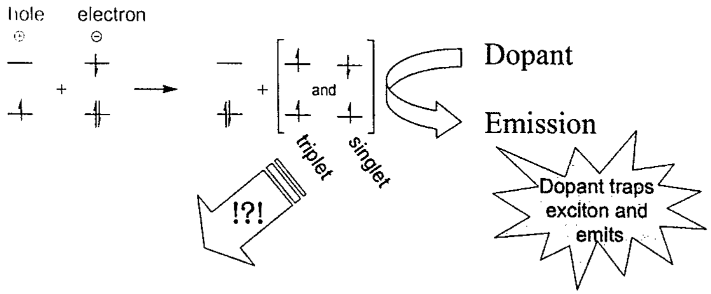
Thermal Stabilities





- ISF/NPD HTL crashes 45°C above the NPD T_g
- Low T_g interface layer is not a problem!

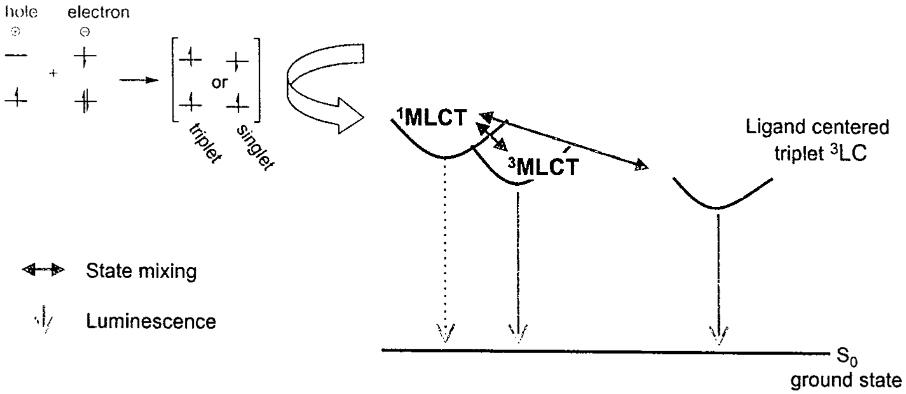
Hole/electron recombination leads to singlet and triplet excitons



- Expected singlet fraction based on simple spin statistics = 25%
- Energy transfers from host/matrix excitonic states to dopant conserve spin.
- Phosphorescence (triplet emission) is formally a forbidden process.

Experimentally determined singlet fraction for Alq_3 based OLEDs = 22±3%
M.A. Baldo, *et.al.*, *Phys. Rev. B* (1999)

Heavy metal facilitated triplet emission

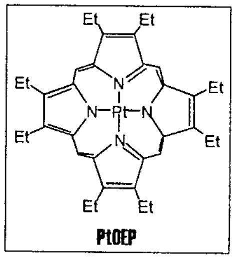


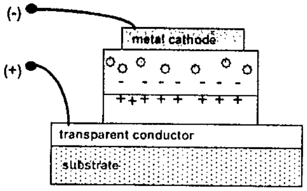
- Strong spin-orbit-coupling mixes singlet and triplet MLCT states, for M = Ir, Pt, Os, Re, *etc.*
- Mixing of triplet states with ^{1}MLCT makes phosphorescence a largely allowed transition, short triplet lifetime

Pt based phosphorescent dye/dopant

- Platinum octaethylporphine (PtOEP) has high phosphorescence quantum efficiency*
  - PL efficiency (phosphorescence) is 0.5 at 298 K (in polystyrene), τ = 91 msec
  - PL efficiency 0.9 at 77K, τ = 130 msec
- Simple, two layer structure gives good eff.
  - 4 % external at low brightness
  - Exclusive PtOEP triplet emission.

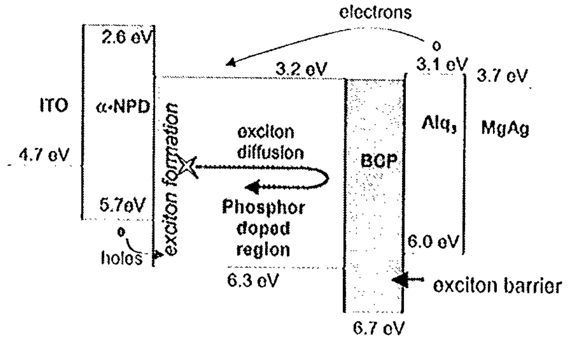
See: M.A. Baldo, *et. al.*, *Nature* (1998)

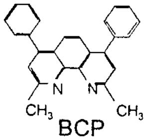




* G. Ponterini, *et al*, *J. Am. Chem. Soc.*, (1983)
* D.B. Papkovski, *Sens. Actuators*, (1995)
* J. Rodriguez, *et al*, *Chem. Phys. Lett*, (1988)

Efficient electrophosphorescent device structure

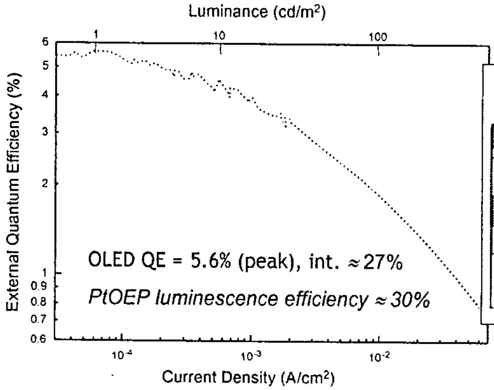


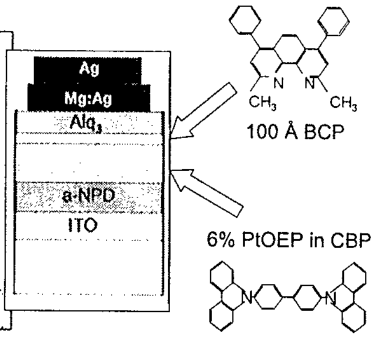


BCP

- Triplet excitons have long lifetimes, leading to long exciton diffusion lengths
  - > 1400 Å for PtOEP
- Blocking layers:
  - prevent exciton diffusion to the electrodes and quenching
  - Confine carrier recombination to the emissive layer

Quantum Efficiencies of PtOEP OLEDs with an Exciton Blocking Layer

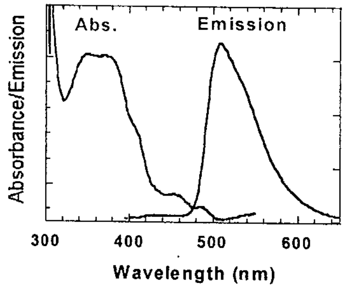


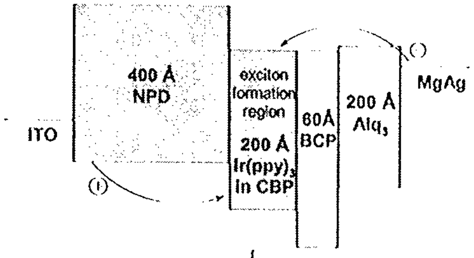


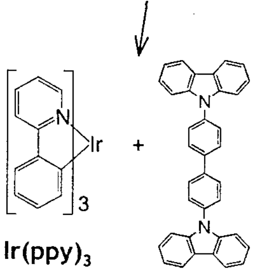
- Q.E. decay as current is increased is due to T-T annihilation
  - $T_1 + T_1 \rightarrow S_0 + S_1$, second order quenching process !!
  - decrease the effects of T-T annihilation by:
    - ⇒ decrease [triplets], lower the doping level: phosphor saturation a problem
    - ⇒ short triplet lifetime will decrease T-T annihilation

See: D. O'Brien, *et. al.*, *Appl. Phys. Lett.* (1999)

Organometallic Ir Phosphor





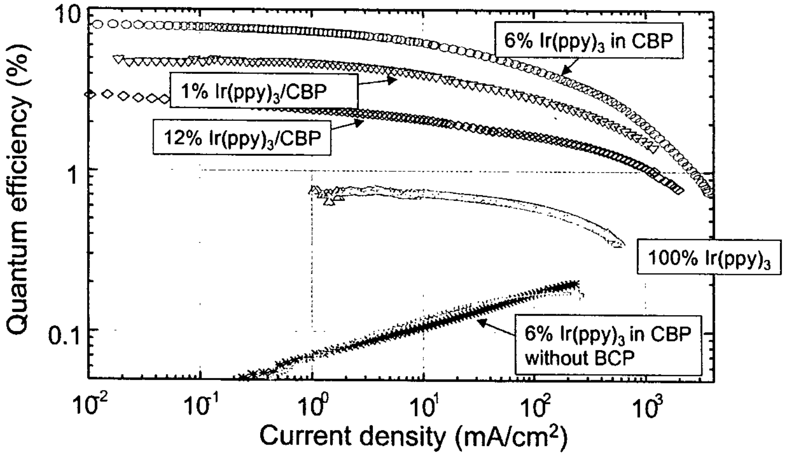


Ir(ppy)₃

- ○ short lifetime: 500ns in CBP
- ○ no fluorescence observed, only phosphorescence (ϕ_{PL} = 0.4) Iridium ⇒ strong intersystem crossing
- ○ R.J. Watts, *et. al.*, *Inorg. Chem.* (1991)

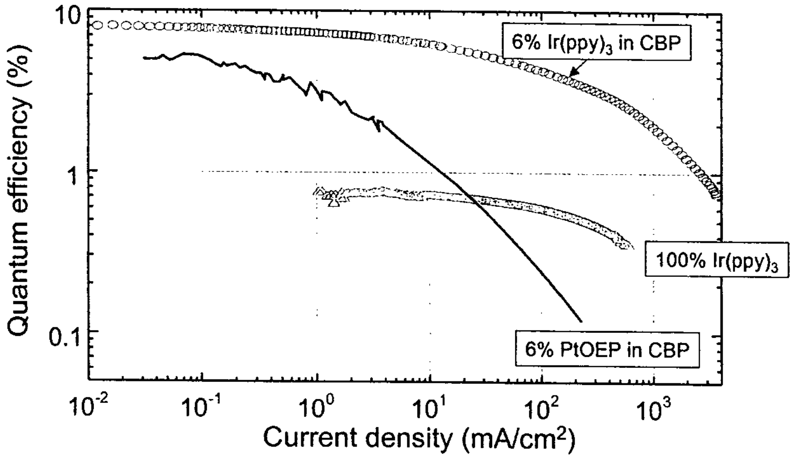
M.A. Baldo, *et. al.*, *Apl. Phys. Lett.*, **1999**

External quantum efficiency of Ir(ppy)$_3$ in CBP



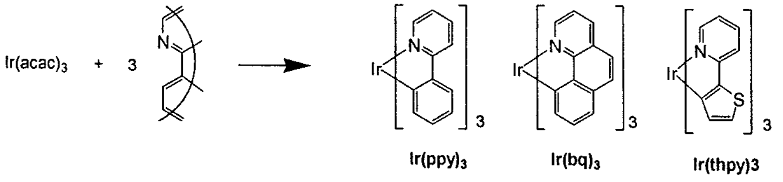
- *ca.* 1/5 of the light is forward scattered, thus η(internal) = 5 x η(external) peak internal efficiency ≈ 40%

External quantum efficiency of Ir(ppy)$_3$ vs. PtOEP in CBP



- PtOEP and Ir(ppy)$_3$ devices have the same structure.

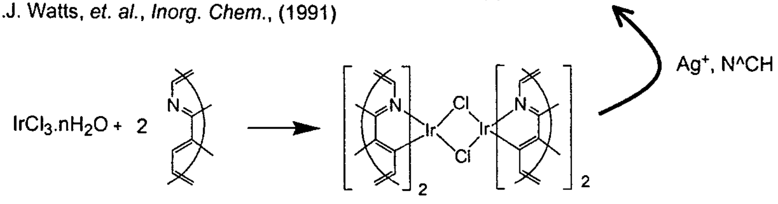
Synthesis of Cyclometallated Ir Complexes



Green EL

typical yield = 30%, reaction only works for ppy, bq and thpy

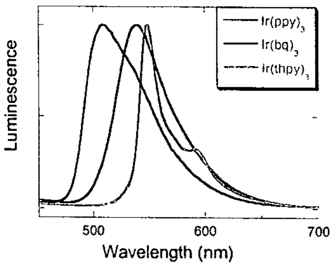
Ir(ppy)$_3$: R.J. Watts, *et. al.*, *Inorg. Chem.*, (1991)



typical yield > 90%, *not emissive in solution or solid state*

M. Nonoyama, *Bull. Chem. Soc. Jpn.* (1974)

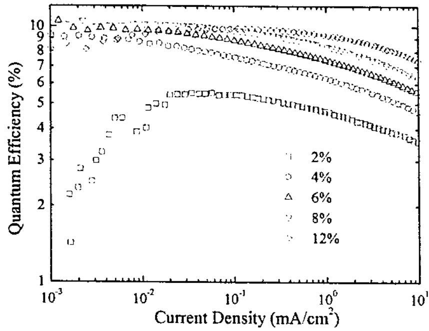
Electroluminescent Spectra of Cyclometallated Phosphors



- All phosphors have τ < 5 μsec
- Spectra constant on increasing bias/current

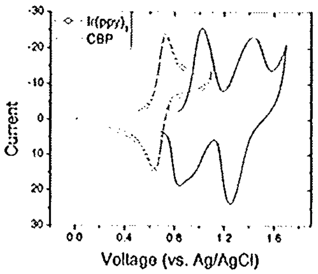
Dopant	peak η_{ext} (%)
Ir(bq)$_3$	10
Ir(thpy)$_3$	4 (unoptimized)

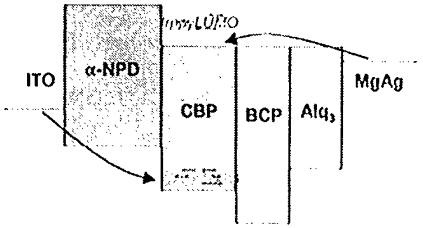
CBP:Ir(bq)$_3$ With BCP Cap



Ir(ppy)$_3$ traps holes in CBP

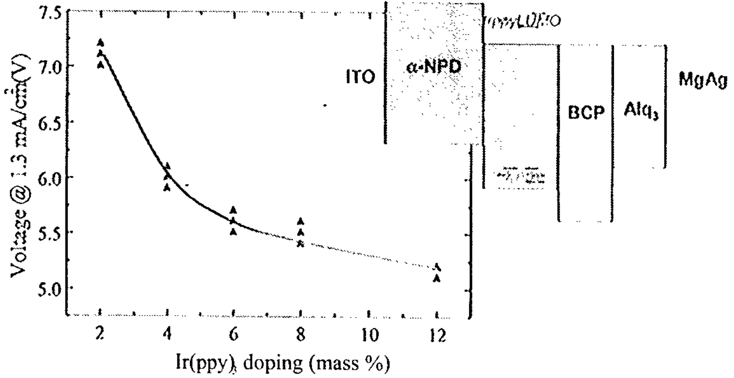
Cyclicvoltamograms of Ir(ppy)$_3$ and CBP





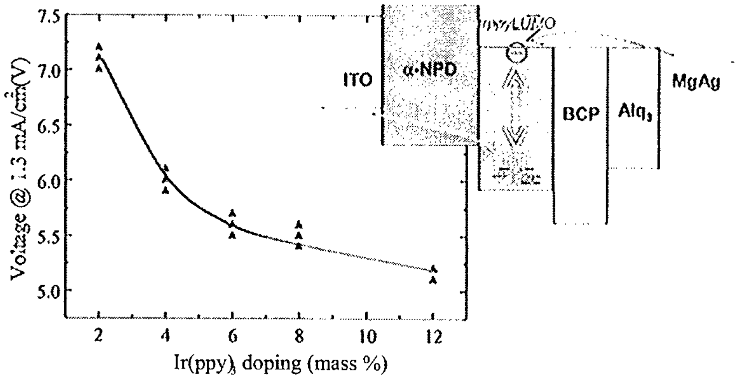
- Ir(ppy)$_3$ HOMO is 300 mV above the CBP HOMO
  - Same picture from both UPS and electrochemical measurements
- Ir(ppy)$_3$ reduction is 3 V above oxidation, *i.e.* Ir(ppy)$_3$ LUMO is above CBP
  - Y. Oshawa, *et. al.*, *J. Phys. Chem.*, **1987**
  - Carrier gap (oxid. – red.) matches the ^{1}MLCT energy

Conduction through Ir(ppy)$_3$ "trap" states



- Holes are carried by the Ir(ppy)$_3$ dopant at doping levels > 5%
- Hole leakage into Alq$_3$ will be dominant without hole blocker (BCP)
- All holes are localized on dopants, hole-electron recombination at the dopant
- Same Behavior is observed for other Ir based dopants (Ir(*bq*)$_3$ and *ppy*$_2$Ir(acac))

Conduction through Ir(ppy)$_3$ "trap" states



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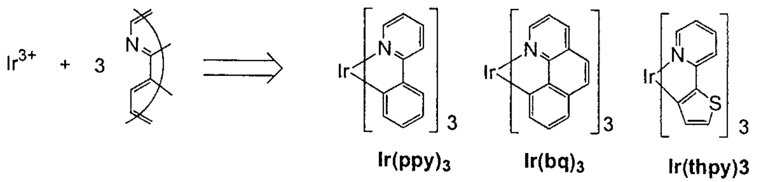
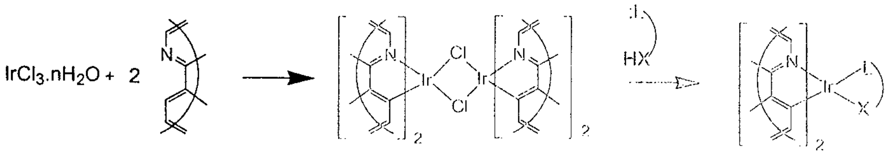
Synthesis of Cyclometallated Ir Complexes



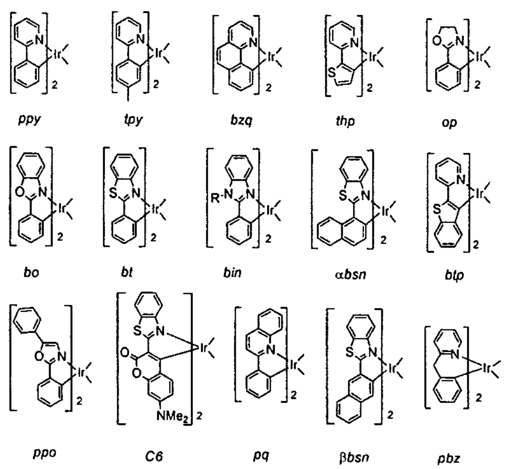
Reactions only work for ppy, bq and thpy ligands (and substituted derivatives)

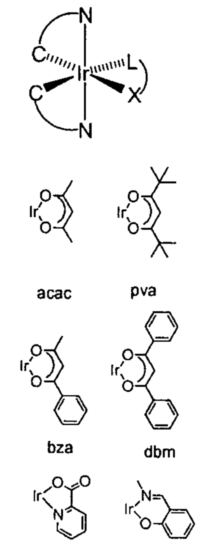


typical yield > 90%, similar yields for a wide variety of ligands

1st step: M. Nonoyama, *Bull. Chem. Soc. Jpn.* (1974)

Phosphorescent $(C\hat{}N)_2Ir(LX)$ Complexes

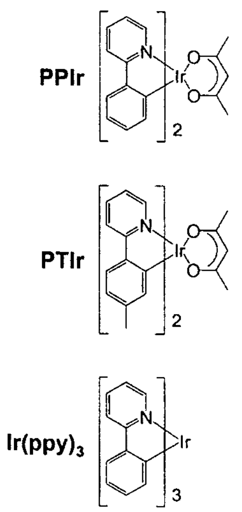


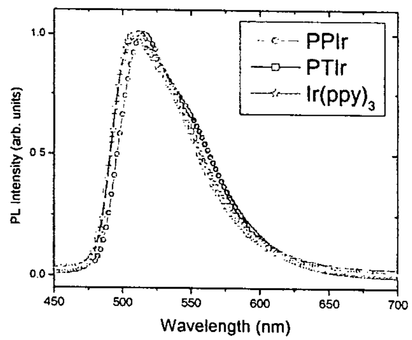


All acac cpds. emit with μsec lifetimes and ϕ_{PL} = 0.2-0.7

S. Lamansky, *et. al.*, *J. Am. Chem. Soc.* (2001)

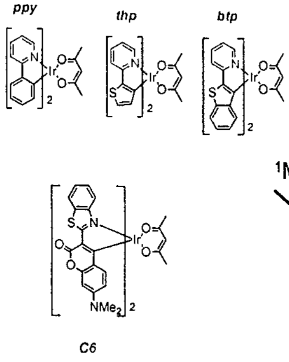
PL spectra of PPIr and PTIr

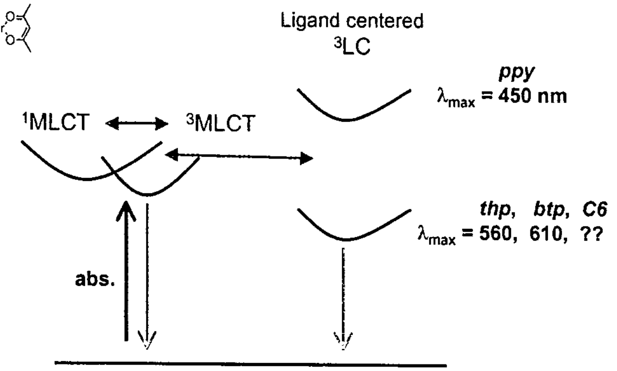




- PPIr and PTIr give solution PL identical to Ir(ppy)$_3$
- Similar volatility (sublimation temps.) for all three complexes
- Same lifetime (2 μsec) and Φ_{PL} (0.4-0.5) for all three

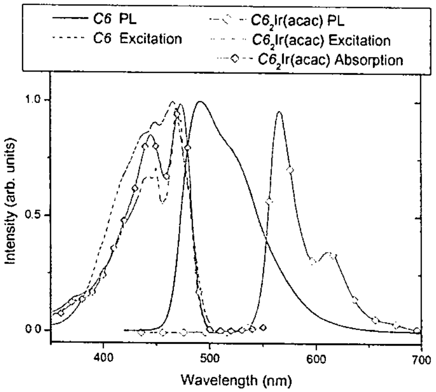
MLCT *vs.* LC excited states

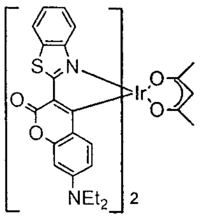




- MLCT energy similar for *ppy*, *thp*, *btp* (450-475 nm).
- The choice of ^{3}MLCT or ^{3}LC emitting state depends on which is lower in energy
- Small Stokes shift is expected for MLCT emission.

$C6_2$Ir(acac) Excitation and Emission

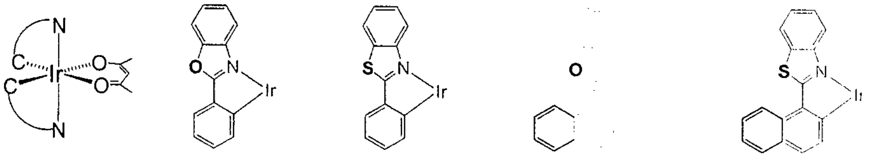




$C6_2$Ir(acac)
C6 is shown in blue

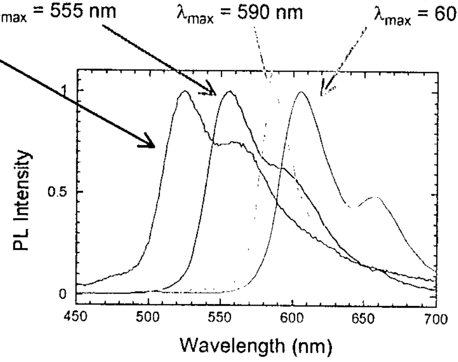
- Coumarin 6 (*C6*) is a common green laser dye, used to fabricate green fluorescent OLEDs
- When this complex is cyclometallated to Ir the emission shifts to orange
  - Ir shifts dominant emission process to C6 based phosphorescence
  - Excitation spectra of $C6_2$Ir(acac) show lines for *C6* as well as MLCT transitions for "L_2IrX"
  - η (PL) for $C6_2$Ir(acac) = 0.6 and τ = 14 μsec

Ligand Effects on Emission energy

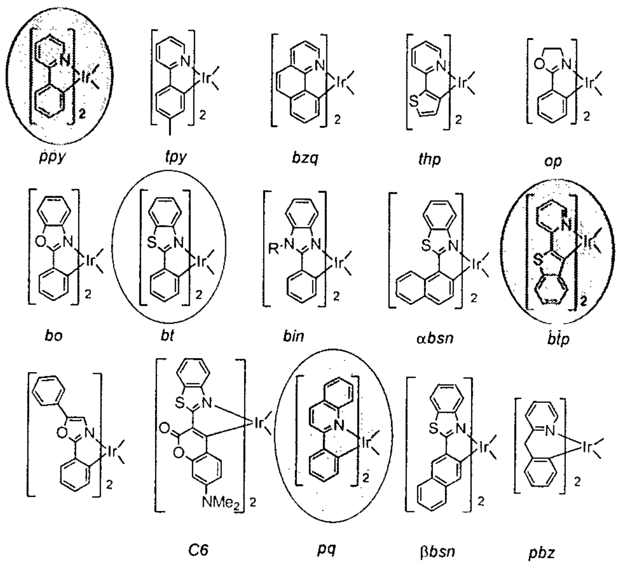


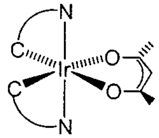
PL eff. = 0.35	PL eff. = 0.4	PL eff. = 0.05	PL eff. = 0.2
τ = 4 μsec (77K)	τ = 2 μsec	τ = 2 μsec	τ = 2 μsec
λ_{max} = 525 nm	λ_{max} = 555 nm	λ_{max} = 590 nm	λ_{max} = 605 nm

- Photoluminescence in solution
- Lifetime in polystyrene at R.T.
- Bathochromic shifts for:
  - O ⇒ S
  - phenyl ⇒ napthyl
  - Effect is additive

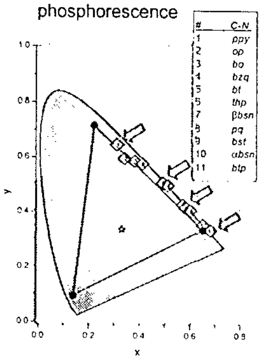


Green, yellow and red phosphors for OLED study

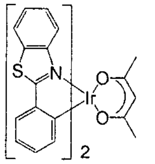




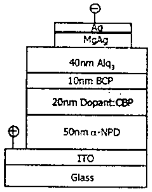
CIE coords. based on phosphorescence

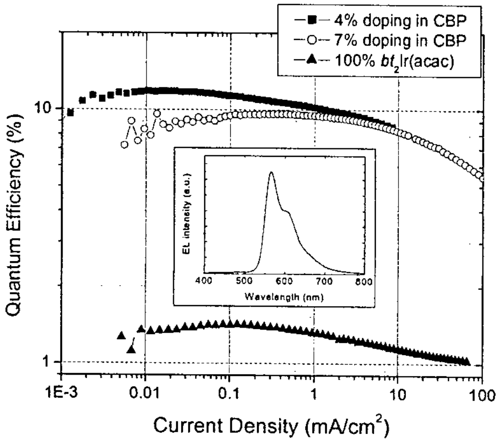


Performance of BTIr doped OLED (yellow emission)



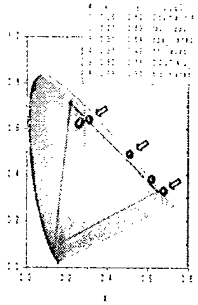
BTIr





- Peak external quantum Efficiency = 11%
- Efficiency with 100% BTIr emissive layer > 1.5%: very weak self quenching

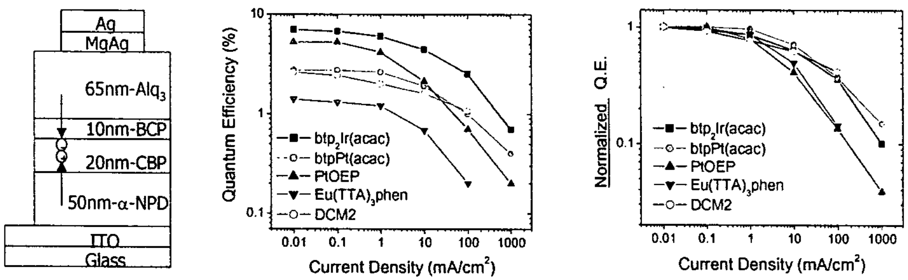
$(C^\wedge N)_2Ir(acac)$ (C^N = ppy, bt and btp) doped (7%) OLED performance



C^N ligand	ppy	bt	btp
EL color	Green	Yellow	Red
Peak wavelength (nm)	525	565	617
Luminance @1 mA/cm^2(cd/m^2)	441	300	62
Drive voltage (V) @ 1 mA/cm^2	7.2	7.3	8.5
Ext. quantum efficiency (%) @ 1 mA/cm^2	10.0	9.7	6.6
“ @ 10 mA/cm^2	7.6	8.3	6.0
“ @ 100 mA/cm^2	5.4	5.5	4.6
Power efficiency (lm/W) @ 1 mA/cm^2	18	11	2.2

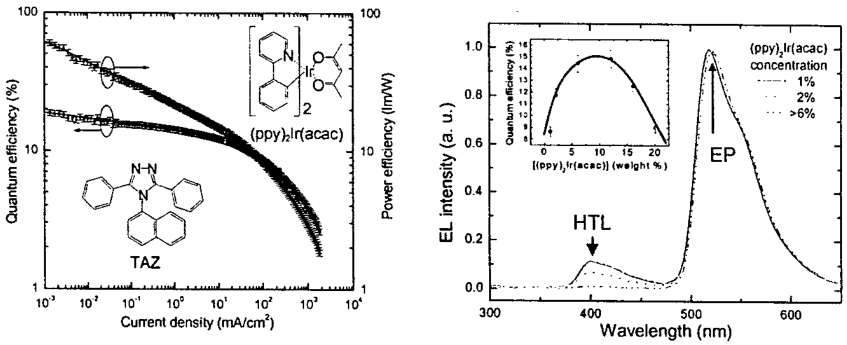
- Similar properties for PQIr (orange) OLED
- All dopants give external eff. > 11 % for optimized structures (CBP host)
- Phosphors can be switched in a “modular” fashion with very little alteration of device performance

Saturated red OLEDs



- Doping concentration optimized for each dopant
- DCM2 device is not red, emission is yellow-orange (low doping concentration)
  - Fluorescence based device, NOT phosphorescence
- btp complexes of Ir give the best performance
  - Highest peak efficiency
  - Slowest drop off in eff. as a function of current density

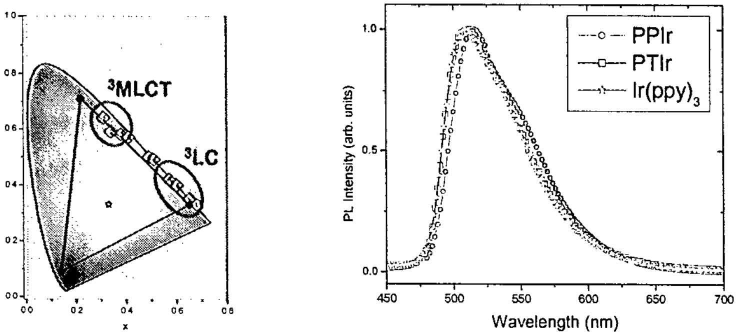
Near 100% Efficiency



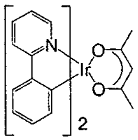
- Device structure: ITO/HTL/TAZ•$(ppy)_2Ir(acac)$/BCP/Alq_3/Li-Al
- Optimal doping concentration = 12%: high eff., low drive voltage
- $\eta_{ext} = (19 \pm 1)\%$, $\eta_{int} = (87 \pm 7)\%$, > 60 lum/W
  - η_{ext} = 14% at 1000 Cd/m^2 (2 mA/cm^2)

C. Adachi, *et. al.*, *J. Appl. Phys.*, **2001**

Green Emission from MLCT States

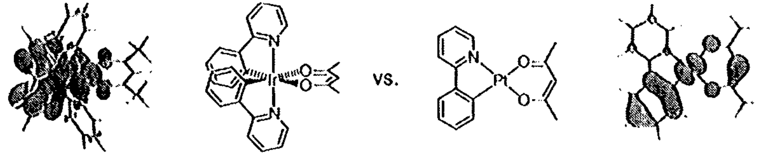


PPIr

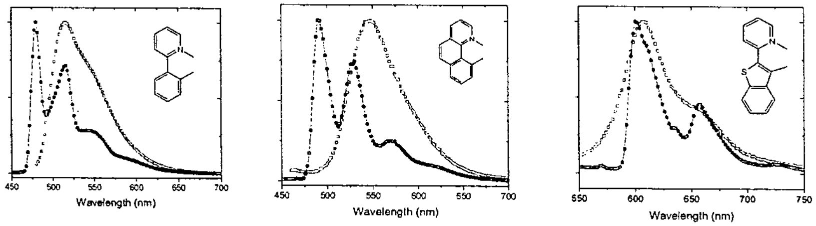


- Changes in C^N primarily affect ^{3}LC, tune green → red
- Emission for *ppy* emitters results primarily from a metal centered transition, ^{3}LC state for *ppy* λ_{max} = 450 nm
- Blue shifted MLCT ⇒ more ^{3}LC character

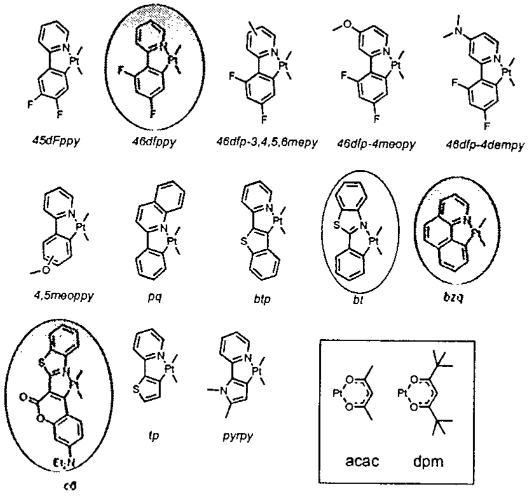
LPt(acac) Compared to L_2Ir(acac) Phosphors

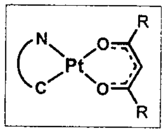


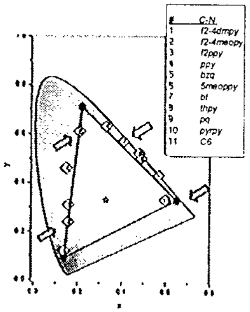
- MO pictures from DFT calculations, Spartan package
- Emission spectra LPt(acac) complexes are shown in blue and L_2Ir(acac) complexes in red.
- All LPt(acac) complexes have lifetimes of 5-10 μsec, ϕ_{PL} = 0.05-0.25 (solution, 298K).
- Complexes with MLCT excited state show significant blue shift, L = *ppy, bzq*.



Cyclometalated Platinum Complexes

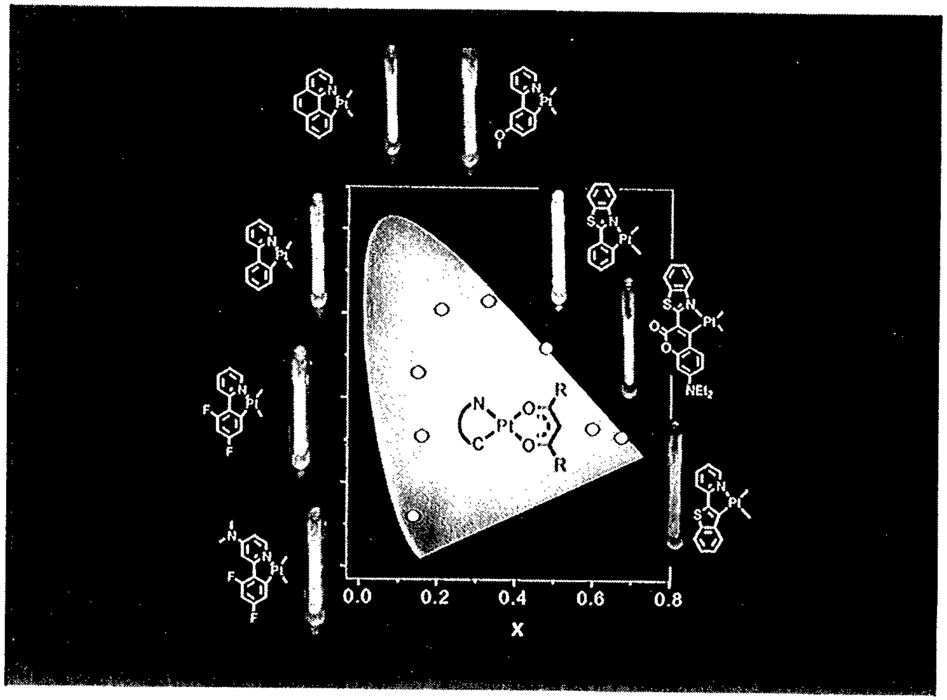




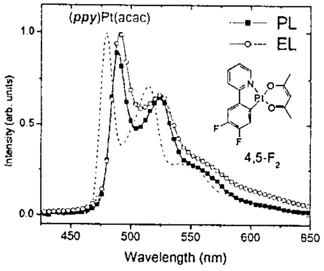


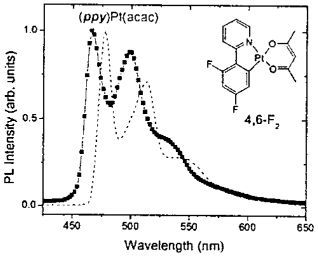
#	C-N
1	f2-4dmpy
2	f2-4meopy
3	f2ppy
4	ppy
5	bzq
5	5meoppy
7	bt
8	thpy
9	pq
10	pyrpy
11	C6

- Pt complexes have similar photophysics as the Ir analogs

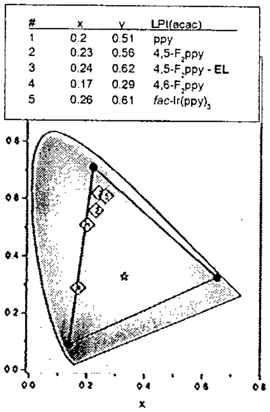


F_2-*ppy*Pt(acac) PL and EL



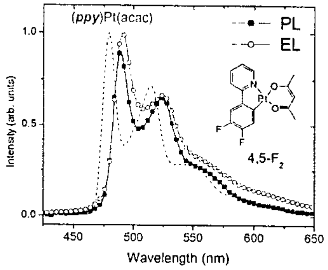


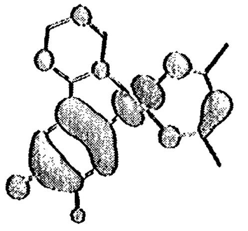
- PL and EL spectra nearly identical for 4,5-F_2-*ppy*
- 4,5- substitution gives red shift (rel. to ppy)
- 4,6- gives blue shift



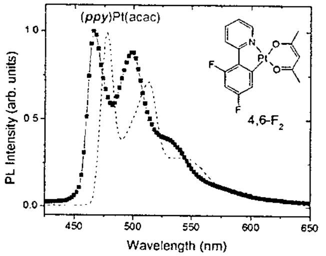
#	x	y	LPt(acac)
1	0.2	0.51	ppy
2	0.23	0.56	4,5-F_2ppy
3	0.24	0.62	4,5-F_2ppy - **EL**
4	0.17	0.29	4,6-F_2ppy
5	0.26	0.61	*fac*-Ir(ppy)$_3$

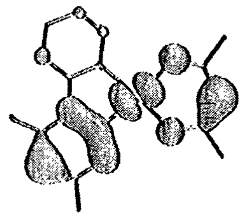
F_2-*ppy*Pt(acac) PL and EL





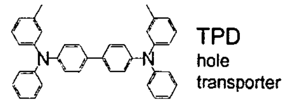
Weak π donation *para* to Pt raises HOMO: red shift

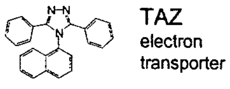


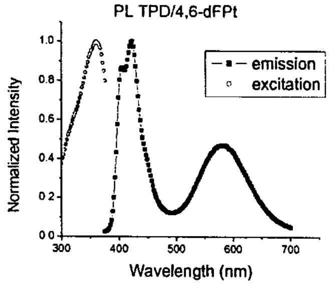


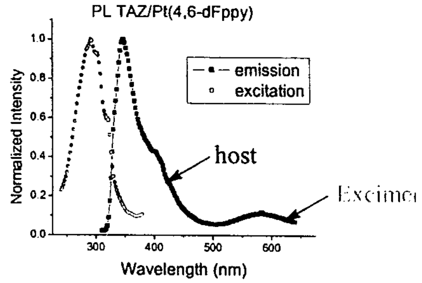
Inductive e⁻withdrawal meta to Pt lowers the HOMO: blue shift

PL of Pt(4,6-dFppy)(acac) in OLED host materials

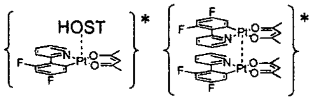






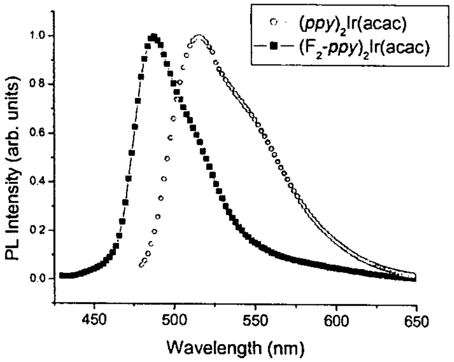


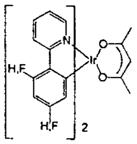
- TPD is a common HTL, TAZ is a common ETL
- Only TAZ/TPD and excimer (580 nm) emission in both hosts
- Identical red emission in both HTL and ETL suggests excimer and not exciplex

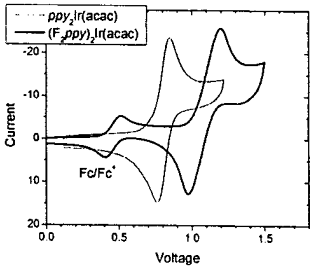


exciplex **excimer**

$(4,6\text{-}F_2\text{-ppy})_2$Ir(acac) solution PL/electrochemistry

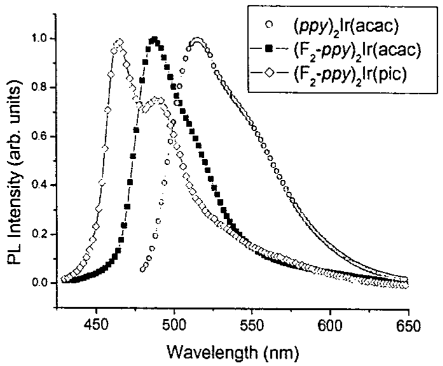


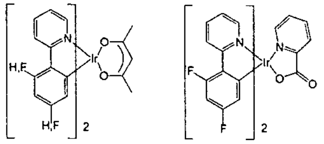


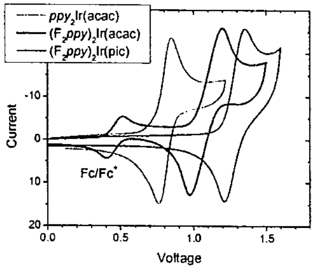


- Octahedral center ⇒ decrease exciplex formation
- F substitution leads to lowering HOMO, and blue shift in emission (MLCT)
  - 275 mV shift in the oxidation potential
  - 140 mV blue shift in emission

$(4,6\text{-}F_2\text{-}ppy)_2$Ir(LX) solution PL/electrochemsitry

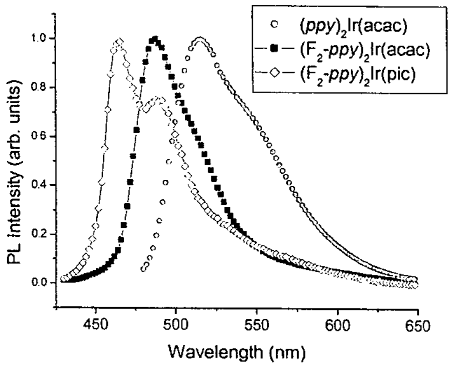


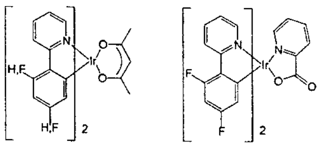


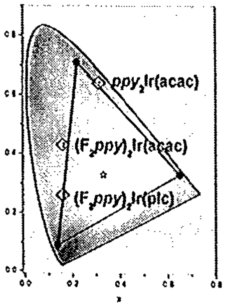


- pic substitution leads to further lowering HOMO, and blue shift in emission
  - 475 mV shift in the oxidation potential
  - 275 mV blue shift in emission
- Emission spectrum consistent with MLCT + $^3\pi$–π*

$(4,6\text{-}F_2\text{-}ppy)_2$Ir(LX) solution PL/electrochemsitry

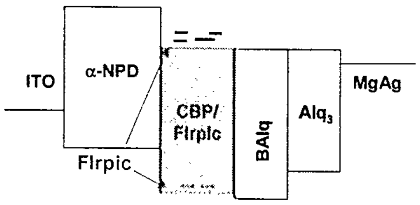


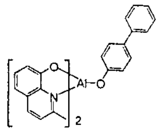




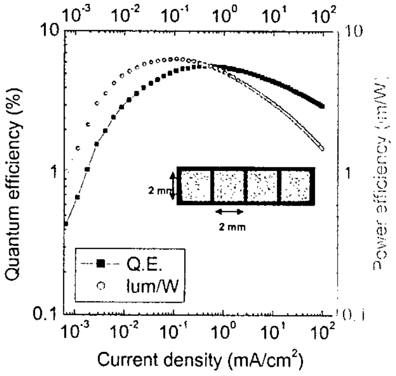
- $(4,6\text{-}F_2ppy)_2$Ir(pic) ⇒ > 200 lumin/optical Watt
- Very similar CIE coords for Pt(acac) and Ir(pic) cpds.
- Octahedral center should decrease excimer/exciplex formation

Blue Electrophosphorescence from FIrpic/CBP





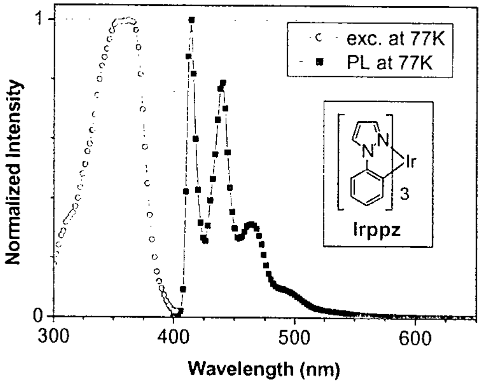
BAlq

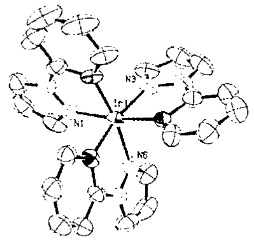


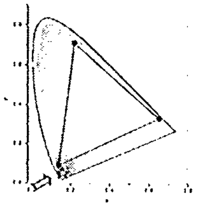
- Emission due solely to phosphorescent dopant
  - No excimer or exciplex
- FIrpic carries electrons in CBP
- Efficiency = 5.5%, > 5 lum/W, 12 cd/A at 100 cd/m^2

C. Adachi, *et. al.*, *Appl. Phys. Lett.* (2001)

Tris(1-phenylpyrazole) Iridium Complexes

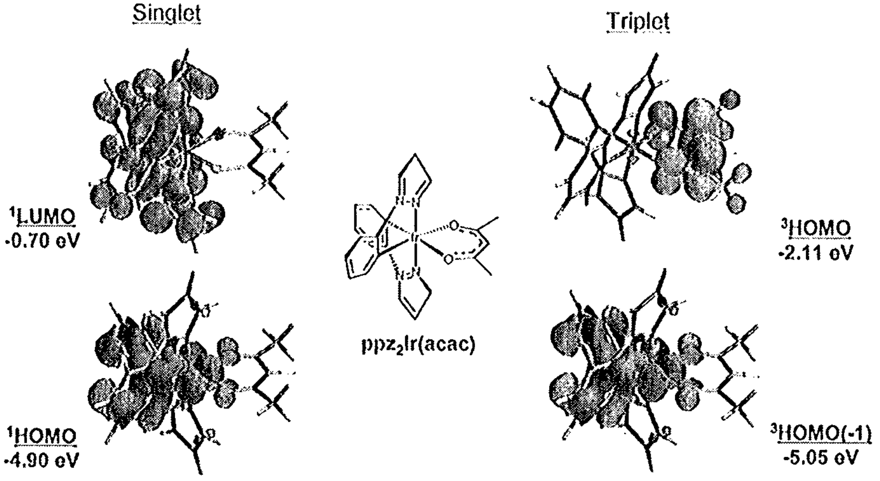






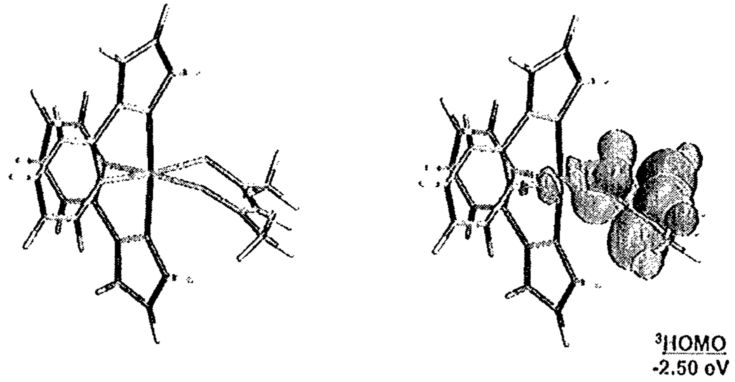
- ppz ligand has high triplet energy
- No luminescence at room temperature
- Are ppzIr derivatives inherently weak emitters?

ppz$_2$Ir(acac) Valence MOs



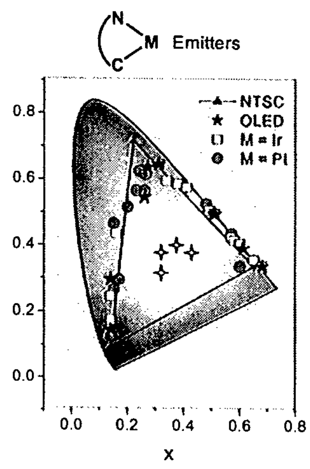
- Triplet is a charge separated state

Minimized Triplet Geometry for ppz$_2$Ir(acac)



- Estimated triplet energy gap:
  - ΔE(singlet-triplet) = 2.40 eV (517 nm) [520 nm, expt.]
- Significant geometry changes in the excited state => quenching
- LX ligands with higher triplet energies are needed to prevent quenching

Summary



- Careful control of the formation, confinement and relaxation of excitons can lead to highly efficient OLEDs
  - Metals are good, expensive metals are better
  - Both carrier and exciton trapping at the phosphor are critical for high efficiency
  - Using Ir based phosphors we have demonstrated η_{int} > 90 % for green, > 60% for red, yellow and orange and > 25% for blue
  - Lifetimes for green, orange and red devices > 50,000 hours
- Careful design of ligands in Ir and Pt complexes leads to efficient, highly tunable phosphors for OLEDs
  - Control of the excited state
  - High efficiency regardless of color (blue, green, yellow, red)
  - Blue → Red and White

Acknowledgements

Jason Brooks, Vadim Adamovich, Peter Djurovich, Arnold Tamayo, Jian Li, Drew Murphy, Liza Babayan, Sergey Lamansky, Douglas Loy, Yujian You
Chemistry, University of Southern California

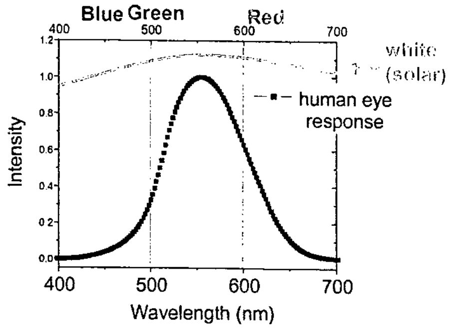
Stephen Forrest, Brian D'Andrade, Marc Baldo, Paul Burrows
Diarmid O'Brien Chihaya Adachi
Electrical Engineering, Princeton University

Raymond Kwong, Mike Weaver, Julie Brown
Universal Display Corporation

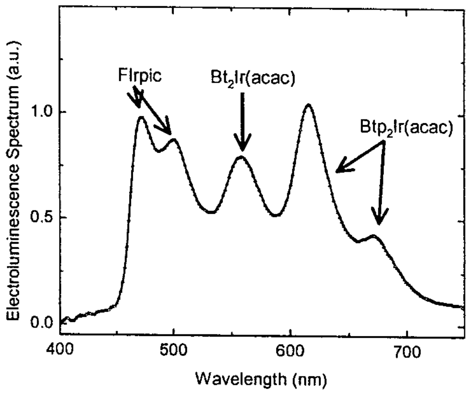
$$ Funding: Universal Display Corporation, NSF, DARPA

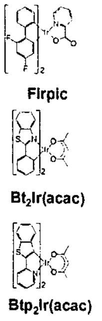
Color Mixing to Achieve White Emission

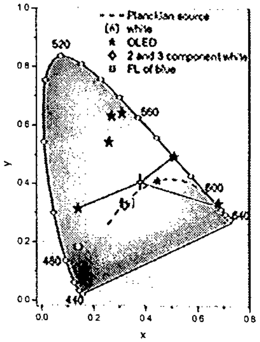
- You need a broad spectrum for good white illumination
- Color mixing with different colored OLEDs
  - Side-by-side arrangement of RGB elements, similar to flat panel display
    - Short R, G and B pixels together
  - Transparent devices can be stacked
    - Pixels on top of pixels with a common substrate
    - Large sheets of transparent R, G and B OLEDS can be stacked to achieve white
- Different dyes can be doped into emissive layer(s) of the OLED
  - multiple dopants in a single layer lead to complications due to energy transfer
  - segregate dopants into separate layers
  - How many emitters are needed?

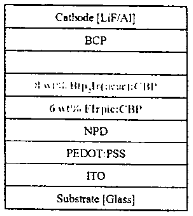


Three phosphor white OLEDs: Each phosphor in a separate layer





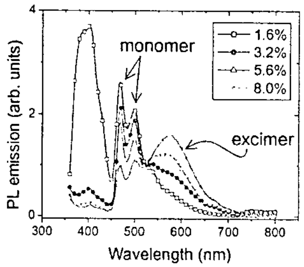


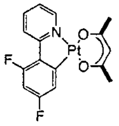


- CIE coordinates = 0.37,0.40, η_{ext} = 5.2%
- maximum luminance = 31 000 cd/m^2
- CRI = 83

B. D'Andrade, *et. al.*, *Advanced Materials* (2001)

Single Dopant Monomer – Excimer Photoluminescnce

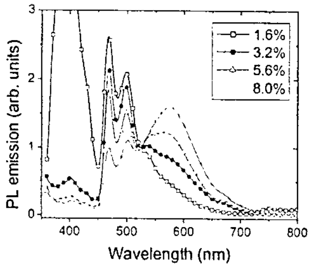


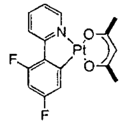


in CBP

- monomer dopant emission at low doping level
- balanced monomer/excimer *ca* 5%
- CBP fluorescence at low doping levels
- Increasing steric bulk can hinder excimer formation
  - could it lead to greater monomer:excimer ratio?

Single Dopant Monomer – Excimer Photoluminescnce





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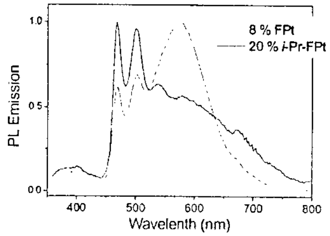
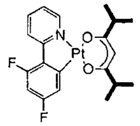
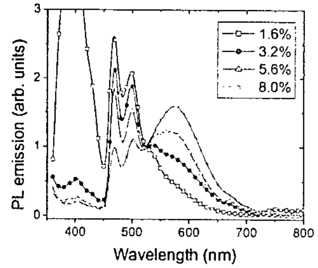


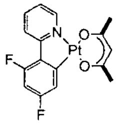


in CBP

- replacing the methyl groups of FPt with *i*-Pr adds significant steric bulk
- Only weak excimer emission is observed at doping levels as high as 20%
- too much steric bulk gives only monomer, we need intermediate steric bulk.

Single Dopant Monomer – Excimer Photoluminescnce





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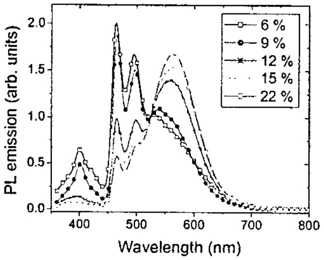
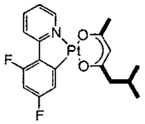
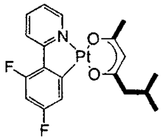




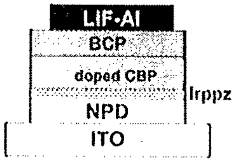
in CBP

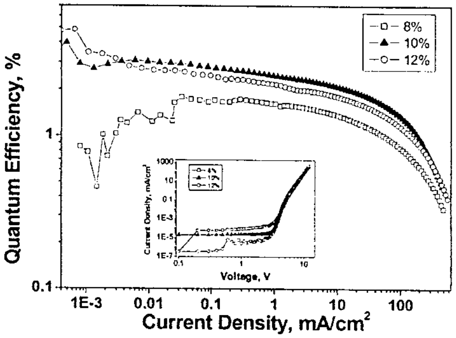
- Now FPt has one methyl and one butyl
- Excimer emission is now observed, and balanced monomer excimer is seen between 9 and 12%, an ideal doping level for OLEDs

High Efficiency Single Dopant WOLEDs



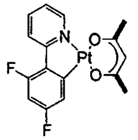
- doped luminescent layer
- only 4 organic layers and one dopant



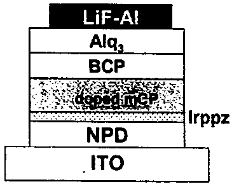


Transfer is still endothermic

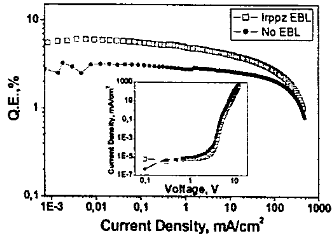
High Efficiency Single Dopant WOLEDs

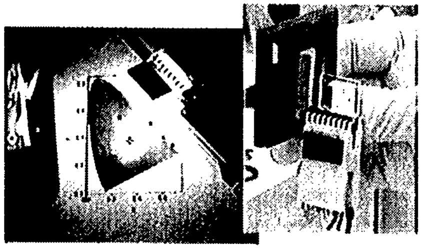


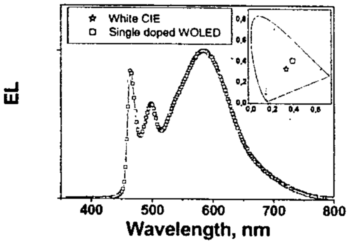
- doped mCP layer



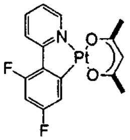
no Irppz: low eff. and NPD emission contribution



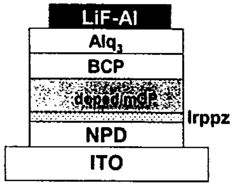




High Efficiency Single Dopant WOLEDs



- doped mCP layer



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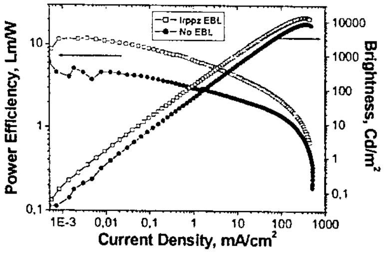
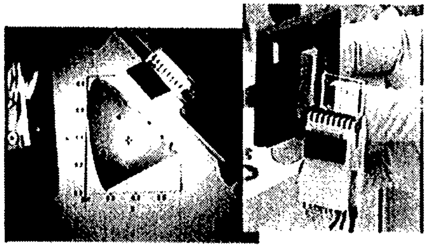




- Q.E = 6% , 12 lum/W @ 1 cd/m²
- Q.E.= 4.5% , 5.1 lum/W @ 500 cd/m²

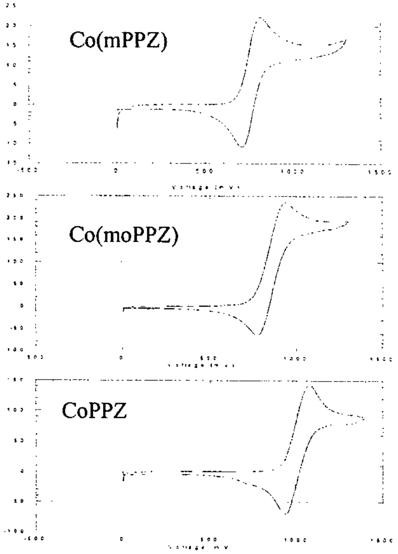
Cyclic Voltammetry and Ultraviolet Photoemission Data

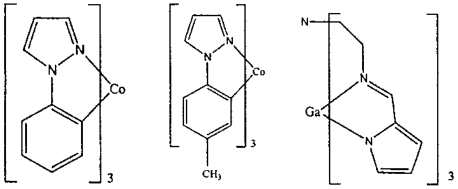
Co(III)PPZ ⟶ Co(IV)PPZ$^+$

The electron-rich phenylpyrazole ligand stabilizes the Co(IV) species produced electrochemically.

UPS Data (HOMO)

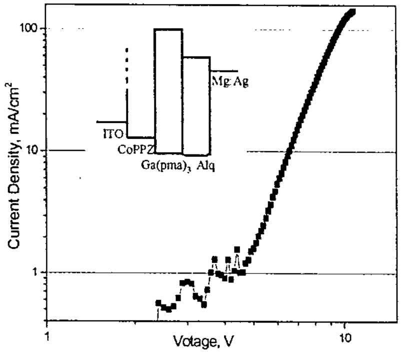
CoPPZ:	5.37eV
Co(mPPZ):	5.38eV
NPD:	5.51eV
Gapma:	5.74eV

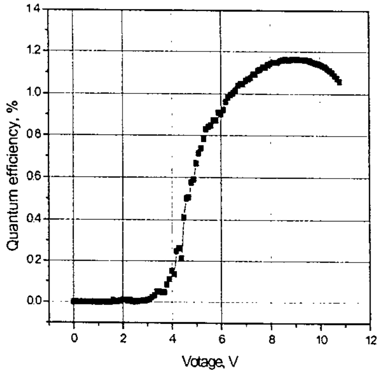




Efficient OLED with ONLY Metal Complexes(1)

ITO/Coppz(400Å)/GaPMAEA(100Å)/Alq(500Å)/Mg:Ag(1000Å)/Ag(400Å)

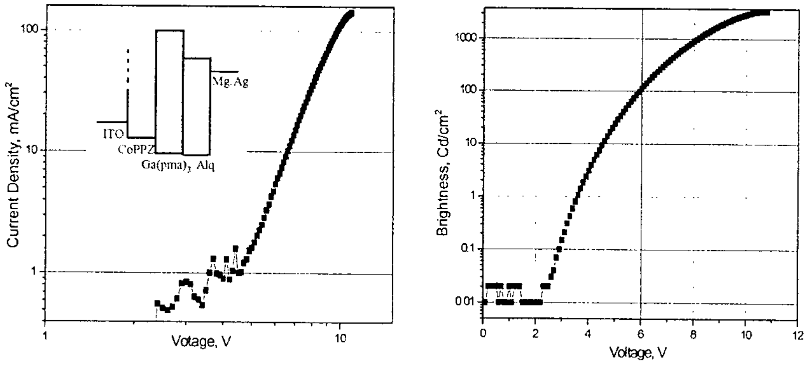




Unfortunately, the device lifetime is poor with a Coppz HTL.

Efficient OLED with ONLY Metal Complexes(1)

ITO/Coppz(400Å)/GaPMAEA(100Å)/Alq(500Å)/Mg:Ag(1000Å)/Ag(400Å)



DARPA HDS Final Program Review

5-3-02

Julie Brown
jjbrown@universaldisplay.com

Universal Display Corporation

HDS UDC Program Objectives

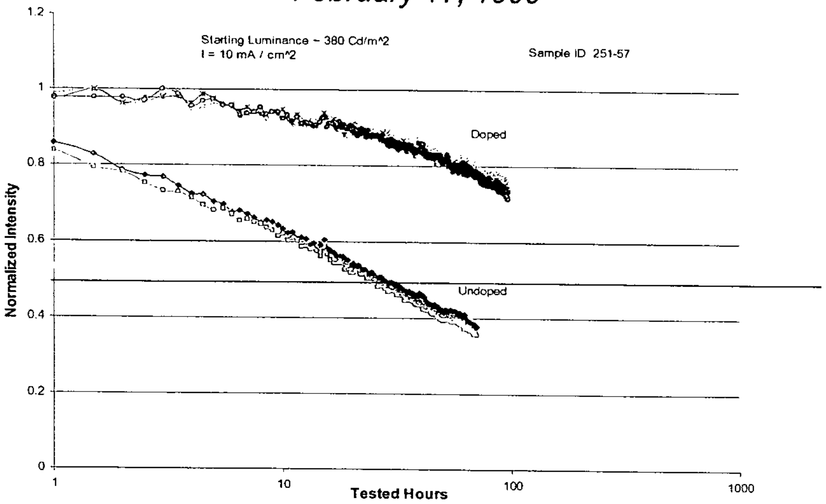
- Demonstrate Reliability
- Fabricate Engineering Prototypes
- Design Pilot Line Facility

Program Elements

- Reliability Task
  - » Life Test System
  - » Process and Packaging
  - » Phosphorescent OLEDs
- Display Prototype Task
  - » Passive Matrix Design
  - » TOLED Passive Matrix Prototype
  - » FOLED Passive Matrix Prototype
  - » Active Matrix Display Prototype
- Pilot Line Facility

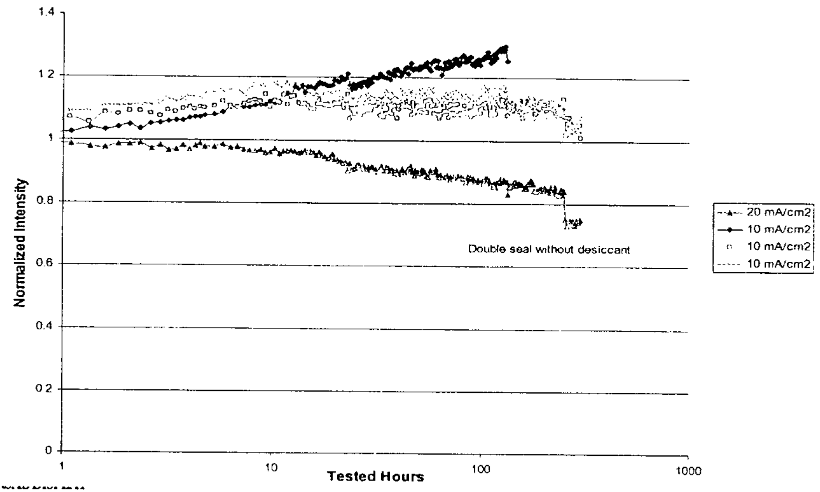
OLED Lifetime: Doped vs Undoped

- February 17, 1999 -



Red PHOLED Preliminary Data

- February 17, 1999 -



Optimization of Electrophosphorescent Devices

-Efficiency

-Device stability

-Color purity

↕

Substrate: surface treatment
Material: hosts, dopants, transporters, blockers, cathode materials
Purity: synthesis, purification
Structure: device architecture, layer thickness, doping concentation
Encapsulation: sealants, getters, curing method
Testing: hardware, software

Red Phosphorescent OLED Lifetime

- April 19, 2000 -

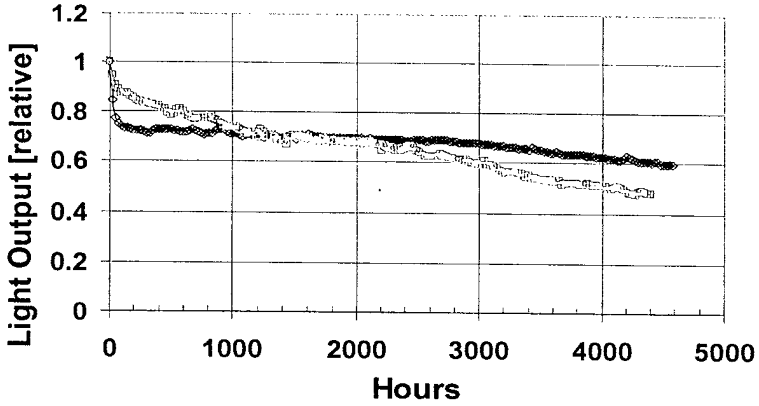
- Device Design

Sample A:
ITO(1500A)/CuPc(200A)/NPD(400A)/CBP:PtOEP(300A)/ Alq_3(200A)/Mg:Ag

Sample B:
ITO(1500A)/CuPc(200A)/NPD(400A)/Alq_3:PtOEP(300A)/ Alq_3(200A)/Mg:Ag

Study of Lifetime Dependence on Phosphor Host

Red PHOLED Operational Stability

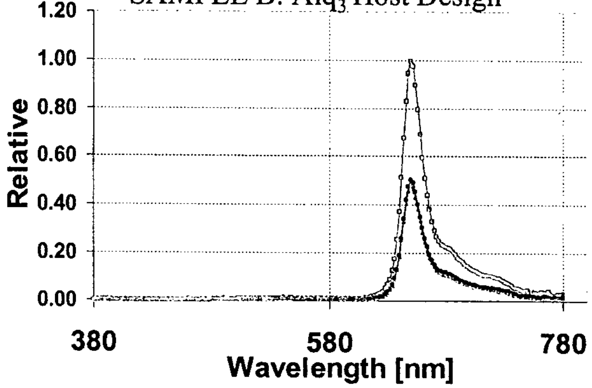


Alq_3 Host: **Lifetime (50%) = 4000 hours**
CBP Host: **Lifetime(50%) = 8000 hours**

April 19, 2000

Red OLED Spectral Response Stability

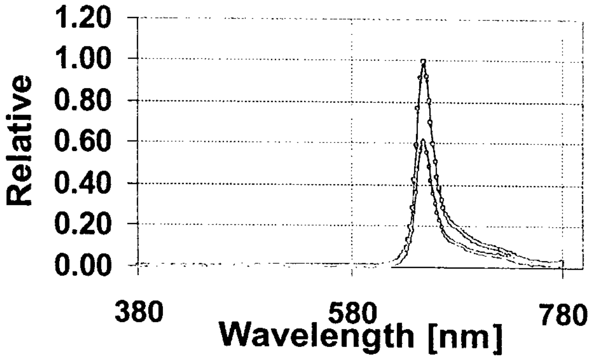
SAMPLE B: Alq_3 Host Design



Comparison of response: t=0 and t=4500 hours

Red PHOLED Spectral Response Stability

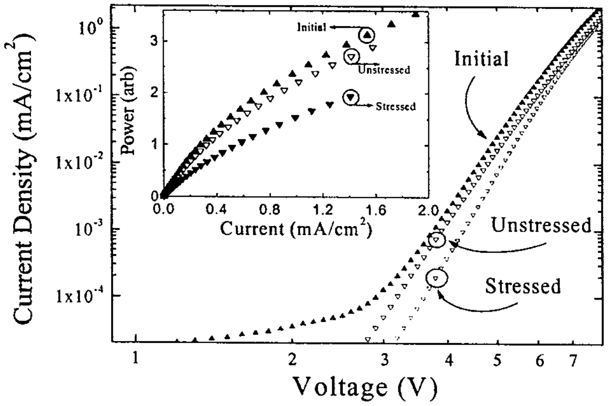
SAMPLE A: CBP Host Design



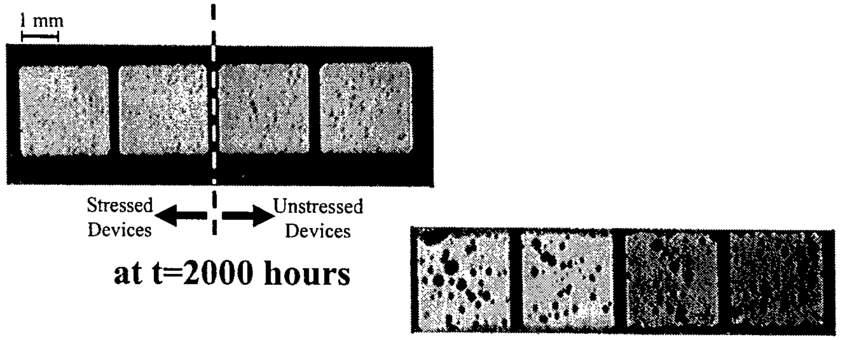
Comparison of response: t=0 and t=4500 hours

Red OLED LIV Stability

Sample A: CBP Host



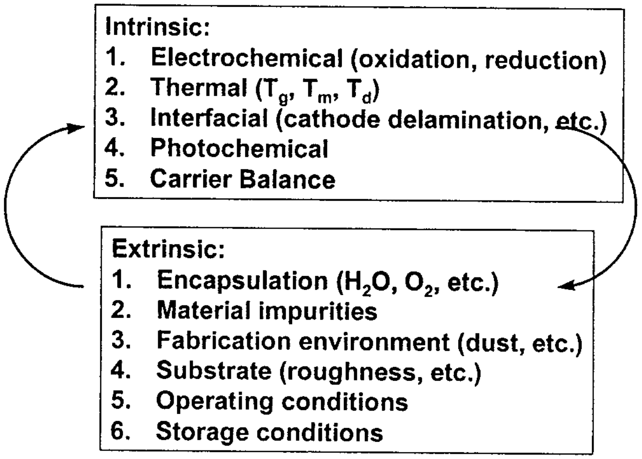
Red PHOLED Package Failure



at t=2000 hours

at t=4000 hours

Device Stability Interacting Factors



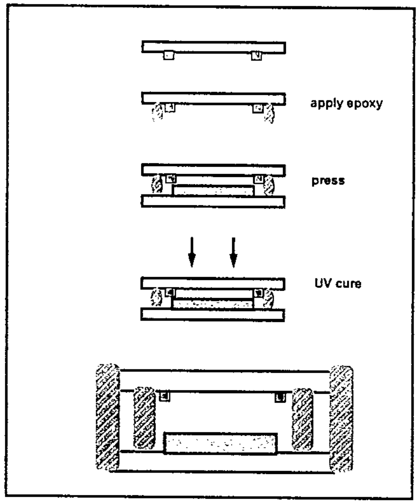
Intrinsic:
1. **Electrochemical (oxidation, reduction)**
2. **Thermal (T_g, T_m, T_d)**
3. **Interfacial (cathode delamination, etc.)**
4. **Photochemical**
5. **Carrier Balance**

Extrinsic:
1. **Encapsulation (H_2O, O_2, etc.)**
2. **Material impurities**
3. **Fabrication environment (dust, etc.)**
4. **Substrate (roughness, etc.)**
5. **Operating conditions**
6. **Storage conditions**

[illegible]

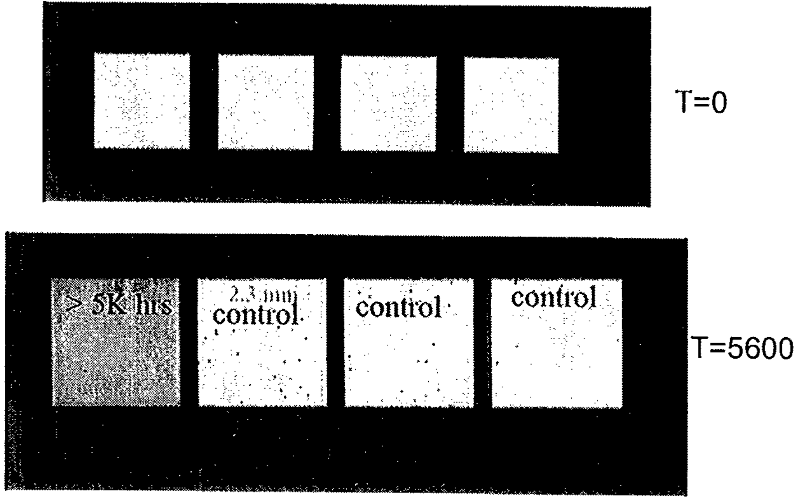
December 14, 1999

Encapsulation Process Flow

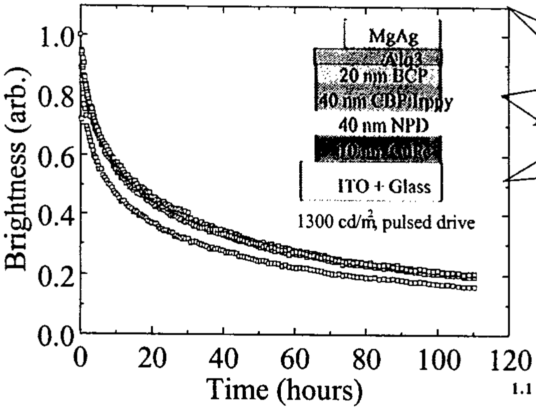


- •Treat glass lid
- •Apply dessicant
- •Apply inner seal epoxy
- •Press lid to display
- •UV cure inner seal
- •Apply outer seal epoxy
- •Cure outer seal

Green PHOLED Package Stability

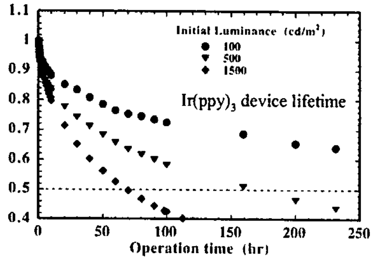


No pixel shrinkage observed after more than 5600 hours @ 500 nits



Are Green Phosphors Stable?

Also, Tsutsui et al.
Jpn. J. Appl. Phys. 38 in press...

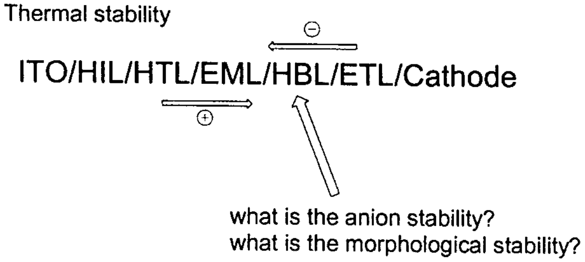


BCP Crystallization ?
Phosphor Degradation?

Hole Blocking Materials

Basic requirements:
- Hole blocking (low HOMO level) and/or low hole mobility
- Electron transporting
- No quenching of the dopant emission

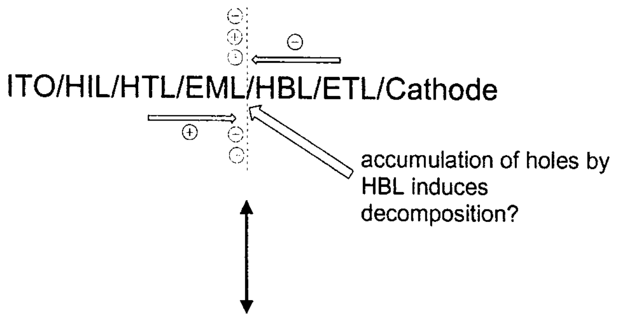
Stability issue:
1. **Anion stability**
2. Thermal stability



ITO/HIL/HTL/EML/HBL/ETL/Cathode

what is the anion stability?
what is the morphological stability?

OLED Design For Long Lifetime



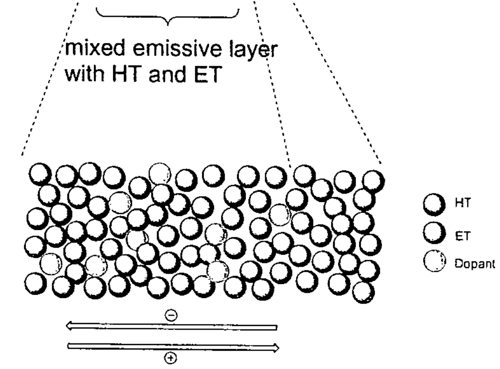
ITO/HIL/HTL/EML/HBL/ETL/Cathode

accumulation of holes by HBL induces decomposition?

What if the interface is absent?

Mixed Layer Devices

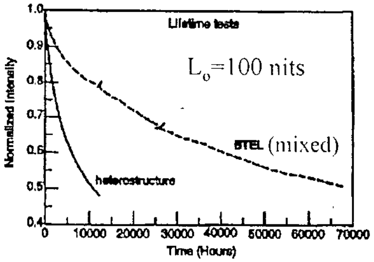
General structure:
ITO/HIL/HT:ET:Dopant/ET/Cathode



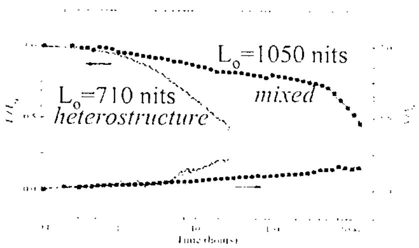
mixed emissive layer with HT and ET

Largely reduced charge accumulation

Previous Mixed Layer Work



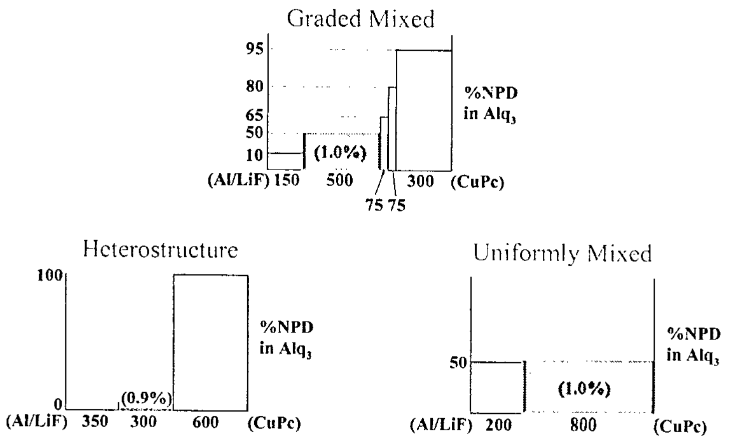
Choong et al., *APL* **75**(2), 172 (1999)



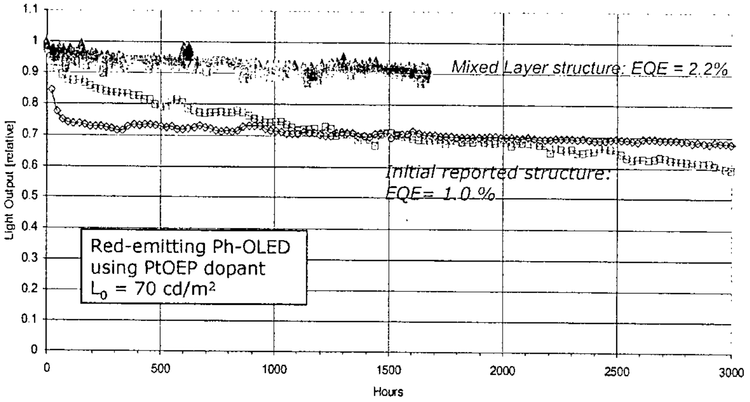
Aziz et al., *Science* **283**, 1900 (1999)

- Naka et al., *Jpn. J. Appl. Phys.* **33**, L1772 (1994)
- Kido et al., *APL* **67**, 2281 (1995)
- Wen et al., *APL* **71**, 1302 (1997)

Device Structures- Current Study



Lifetime Comparison of Deep Red PHOLEDs



Mixed Layer PHOLED Lifetime Extrapolates to > 10^6 hours

Device Structures

Three basic device structures were employed in this study. The data presented correspond to the following structures, which contain a *fluorescent* green dopant (D):

■ Heterostructure

Al
LiF
Alq_3
Alq_3:D (0.9%)
α- NPD
CuPc
ITO

□ Graded Mixed

Al
LiF
α-NPD:Alq_3 (90%)
α- NPD:Alq_3:D ((1:1):1.0%)*
α- NPD:Alq_3 (35%)
α- NPD:Alq_3 (20%)
α- NPD:Alq_3 (5%)
CuPc
ITO

▲ Uniformly Mixed†

Al
LiF
α-NPD:Alq_3 (1:1)
α-NPD:Alq_3:D ((1:1):1.0%)
CuPc
ITO

*NPD:Alq_3=1:1 unless otherwise noted

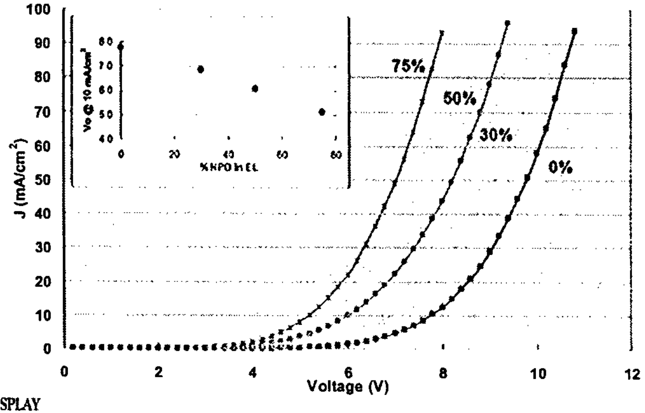
†V-E. Choong et al., *APL* (1999), 75(2), 172

For comparative purposes, the properties of a device with a *phosphorescent* green dopant are also presented:

◇ **PhosG** : EML=CBP:$Ir(ppy)_3$

J-V and V_o Comparison

The dependence of the J-V characteristics on percentage of NPD in the emissive layer of the graded mixed devices is shown below (0% corresponds to the heterostructure). The inset illustrates the decrease in driving voltage V_o with increasing %NPD.



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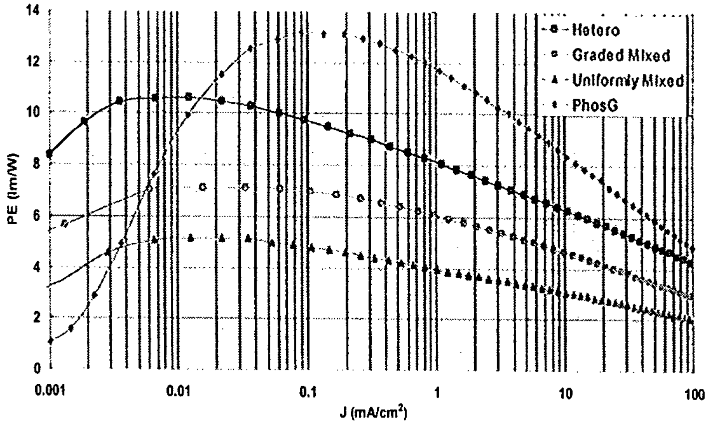
Power Efficiency Comparison



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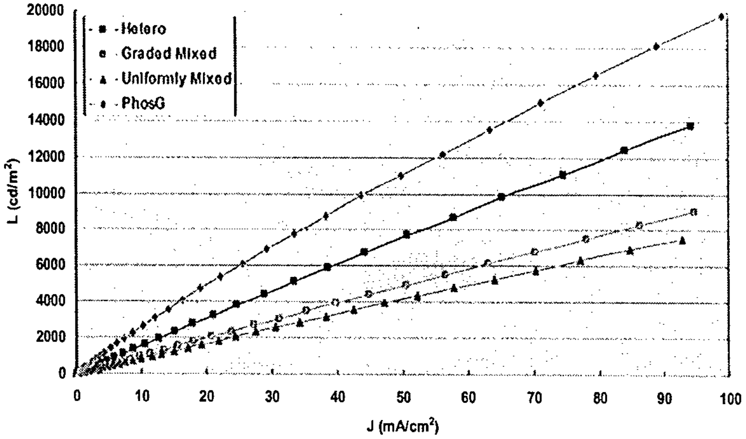
Performance Comparison

Luminance vs. current density of the fluorescent and phosphorescent OLEDs:



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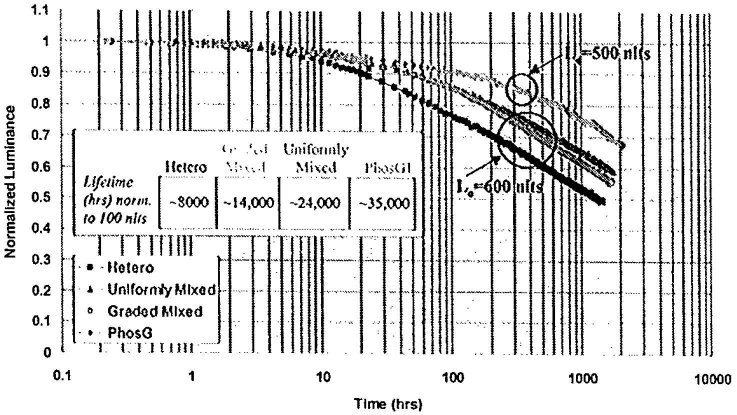
Device Lifetime

The lifetime data (DC, constant current) show that mixing the HT and ET layers improves the lifetime of the device.



	Hetero	Graded Mixed	Uniformly Mixed	PhosG
Lifetime (hrs) norm. to 100 nits	~8000	~14,000	~24,000	~35,000

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Data Summary

	Hetero	Graded Mixed	Uniformly Mixed	PhosG
Power Efficiency (lm/W) @ 100 nits	8.4	6.0	3.8	12.7
Driving Voltage (V) @ 100 nits	5.5	4.5	5.9	6.4
Lifetime (hrs) Normalized to L_o=100 nits (DC, const. J)	~8000	~14,000	~24,000	~35,000

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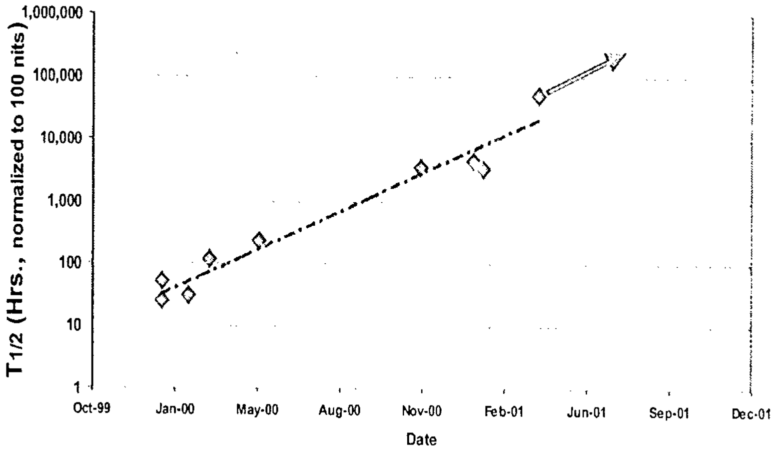
Green PHOLED Lifetime Progress



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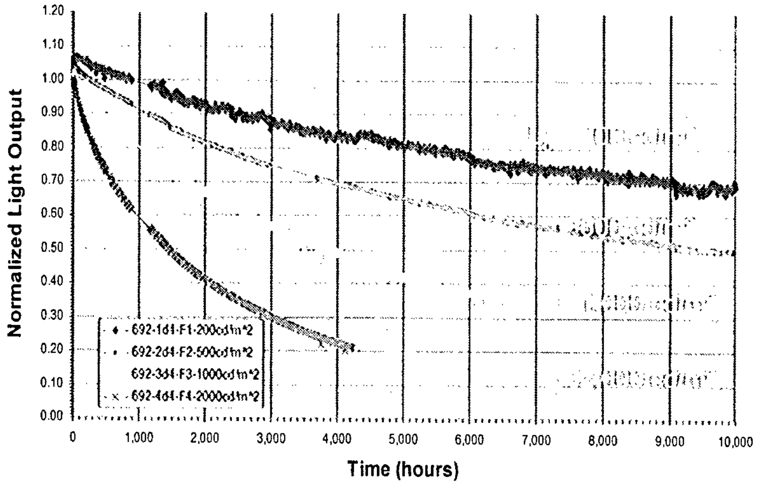
Green PHOLED Lifetime



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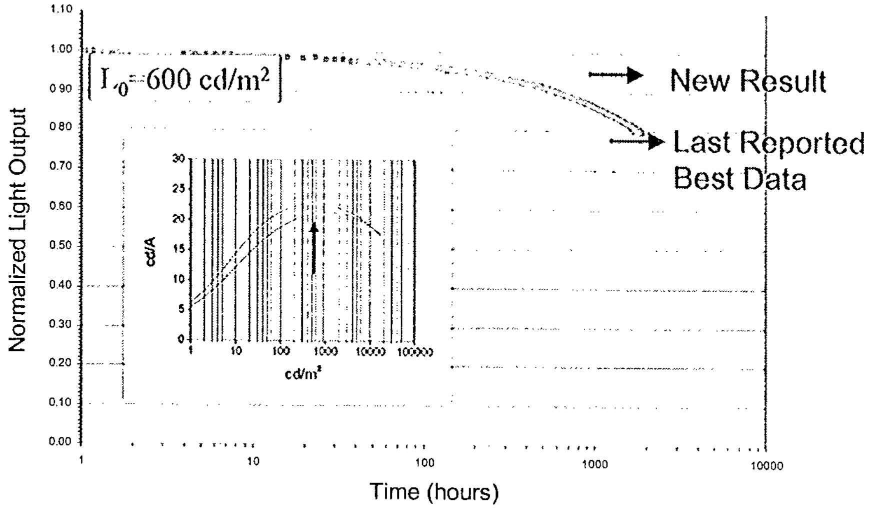
Green PHOLED New Results



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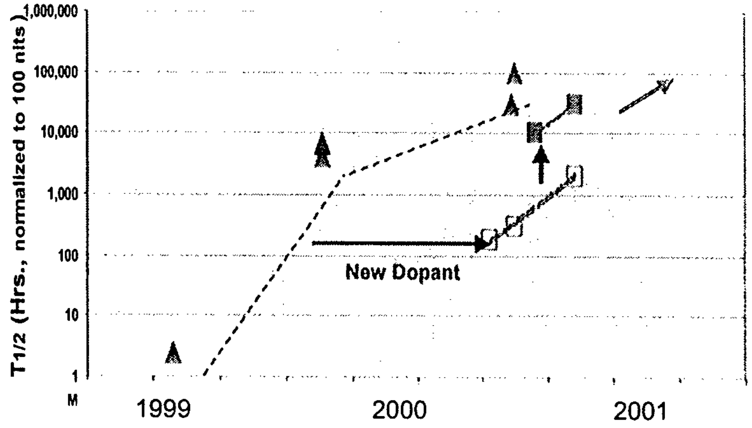
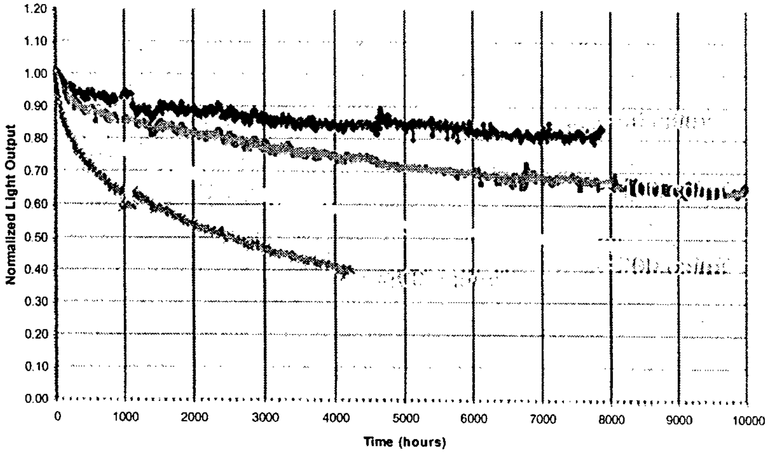
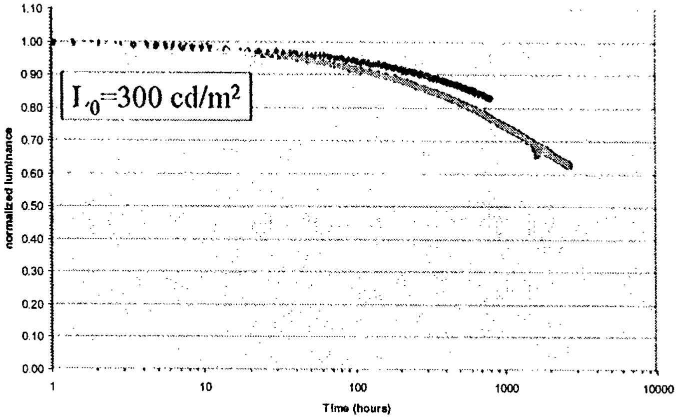
Red PHOLED Lifetime Progress



Mixed Layer Red PHOLED Lifetime



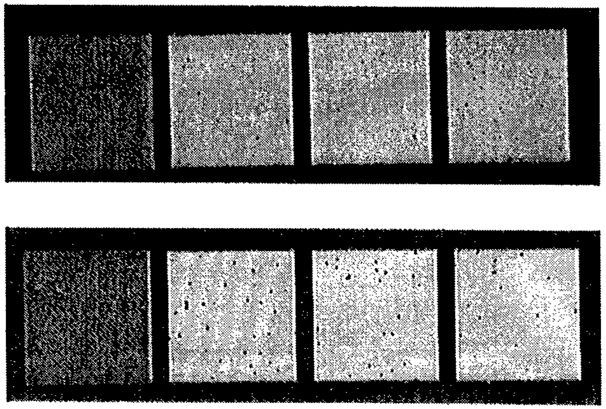
RED PHOLED Lifetime New Results



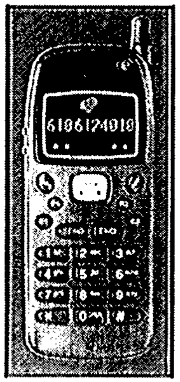
Red and Green PHOLEDs

t= 10,000 hours actual test time

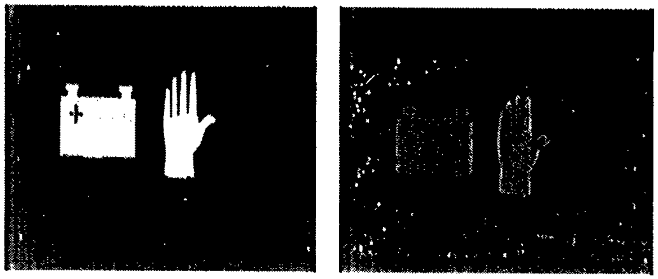
May 1, 2002



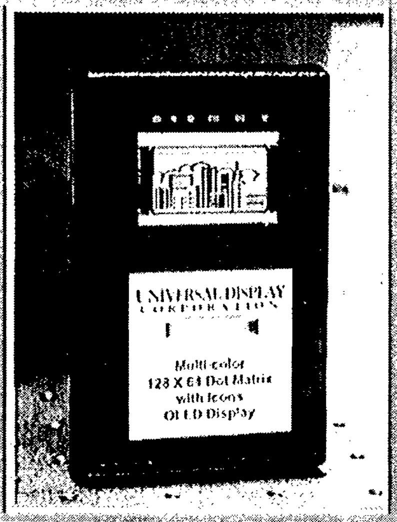
Early Static OLED Prototype

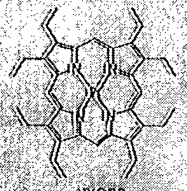


Early SOLED Prototype

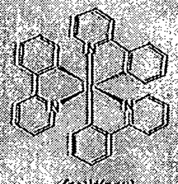


First Passive Matrix Prototype





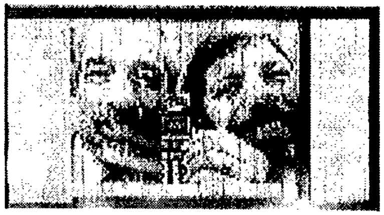
PtOEP



fac-Ir(ppy)$_3$

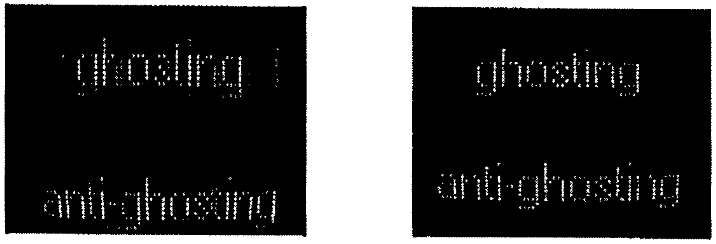
High efficiency materials

Second Passive Matrix Prototype: PM2

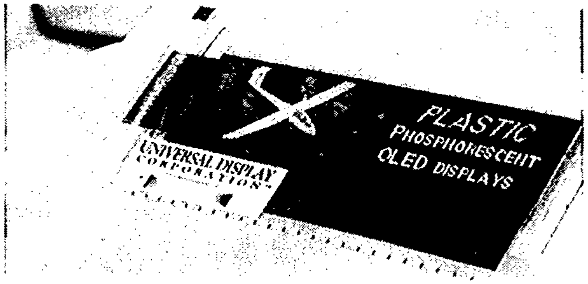


- -128 columns x 64 rows, 80 dpi, 32-level gray scale
- -peak current = 0.2 mA (1/64 duty cycle)
- -driving voltage = 15V
- -pixel active area = H 0.2275 mm x W 0.2475 mm = 0.0563 mm^2
- -pixel spacing = 0.3175 mm x 03175 mm
- -fill factor = 56%
- -average pixel luminance = 660 cd/m^2
  at average pixel current density = 5.6 mA/cm^2
- -nonuniformity <10% (based on VESA FPD std)

Redesign of PM Drive Scheme: Eliminate Ghosting

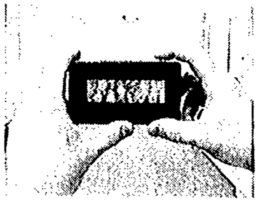


Third Passive Matrix Prototype: PM3



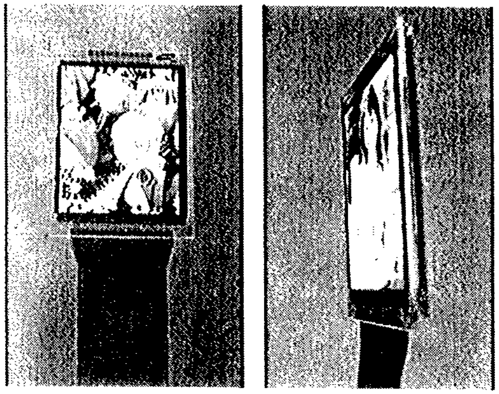
-256 columns x 64 rows, 80 dpi, 256-level gray scale
-peak current = 0.19 mA (1/64 duty cycle)
-driving voltage = 16V typical,
-pixel active area = H 0.2275 mm x W 0.2275 mm = 0.0518 mm^2
-pixel spacing = 0.3175 mm x 0.3175 mm
-fill factor = 51%
-average pixel luminance = 300 cd/m^2 (without circular polarizer) at average pixel current density = 2.9 mA/cm^2
-nonuniformity <10% (based on VESA FPD std)

Digital Camera prototype with OLED display: PM4



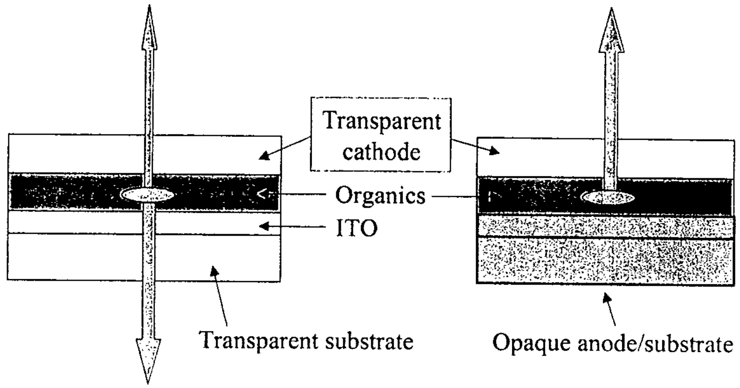
-Configured to be digital camera or compact video monitor with freeze frame
-240 columns x 64 rows, 80 dpi, 64-level pulse width modulation gray scale using off the shelf driver chips
-Peak pixel current = 0.18 mA (1/64 duty cycle)
-Driving voltage = 16V typical, maximum system voltage 18V
-Average pixel luminance = 150 cd/m^2 with circular polarizer at average pixel current density = 2.9 mA/cm^2
-Four hours with fully charged batteries
-Compact size – 4.5" x 2.5" x 1.25"

Samsung SDI 2.2" Full-color Display UDC R/G PHOLEDs



ITEMS	SPEC.
Diagonal size (in.)	2.2
Pixel Format	176 (H) x RGB x 220 (V)
Pixel pitch (μm)	66 x 198
Pixel density (in.$^{-1}$)	128
Panel size (mm^2)	41.976 (H) x 56.232(V)
Aperture ratio	32%
Luminance (w/o polarizer)(cd/m^2)	200 Peak : >300
White Quality	(0.31,0.32)

Transparent *vs.* Top Emission OLEDs


Transparent cathode

Organics

ITO

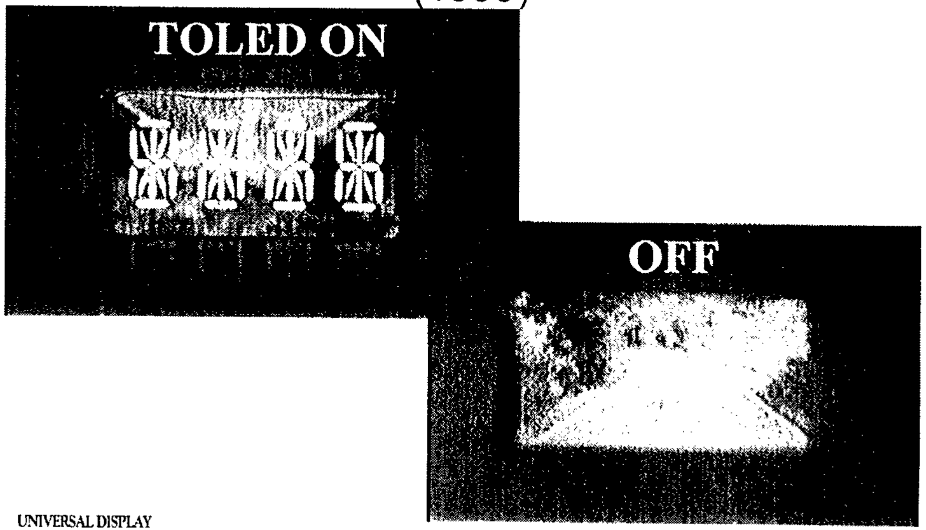
Transparent substrate

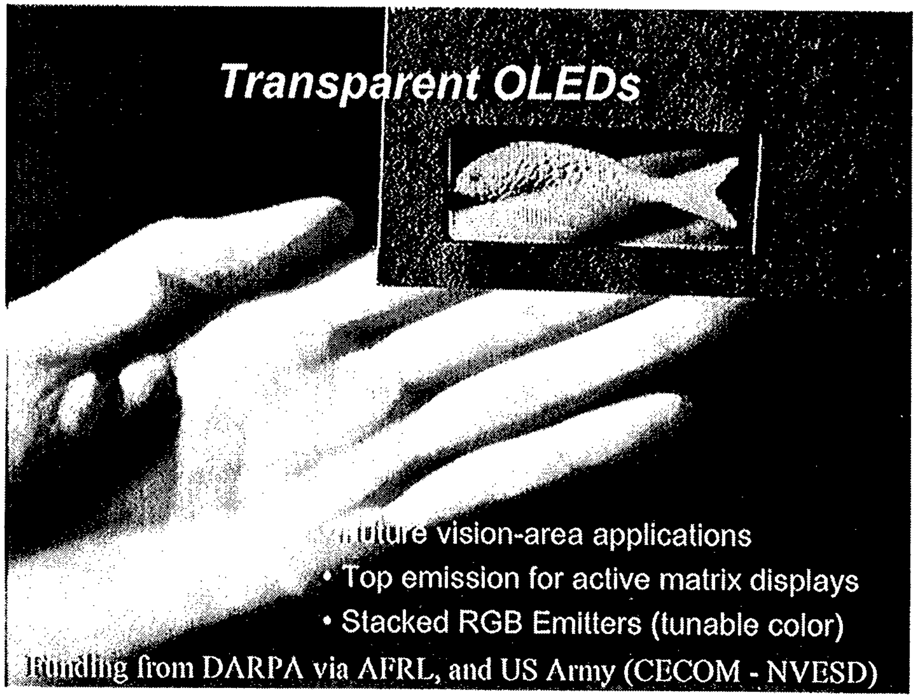
Opaque anode/substrate

Transparent anode and cathode

Opaque anode, transparent cathode

Transparent OLED (TOLED) 1st Prototype (1999)





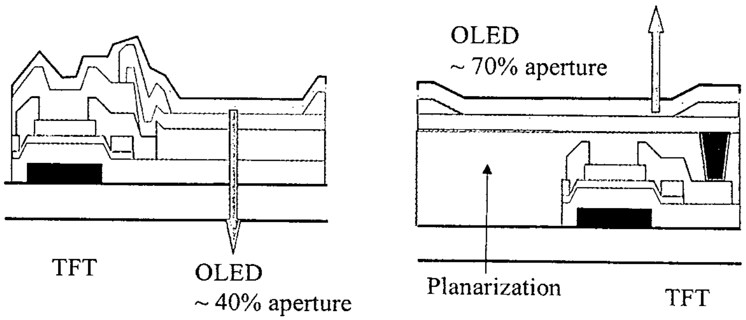
Transparent OLEDs

- Future vision-area applications
- Top emission for active matrix displays
- Stacked RGB Emitters (tunable color)

Funding from DARPA via AFRL, and US Army (CECOM - NVESD)

Technical Merits of Top Emission OLEDs

- Potentially higher efficiency than bottom emission device. We have demonstrated TOLEDs as efficient as the bottom emission device on a reflective anode.
- Allows a higher aperture ratio in AMOLED pixels.


TFT

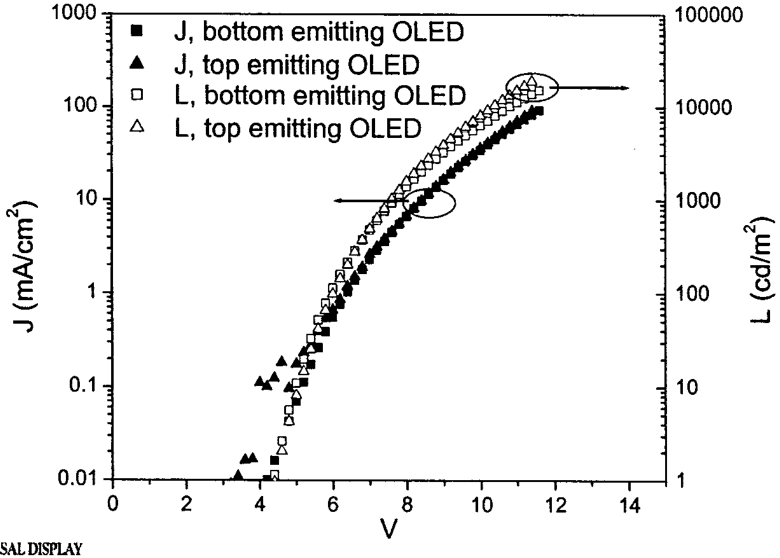
OLED
~ 40% aperture

OLED
~ 70% aperture

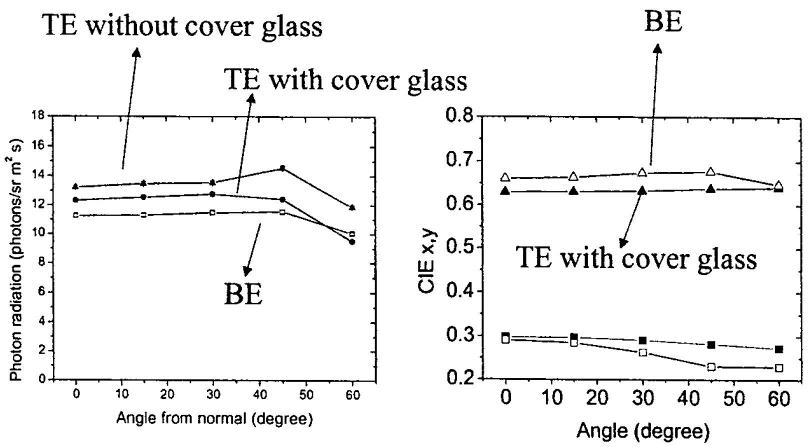
Planarization

TFT

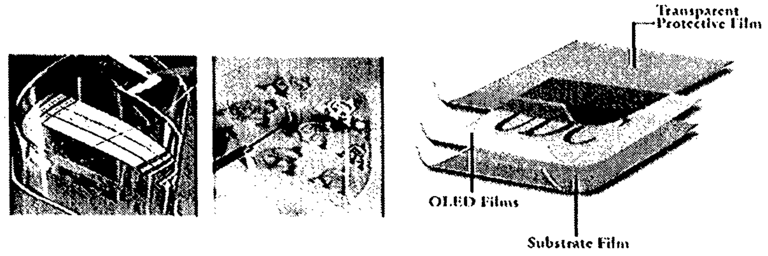
Green Top Emission Devices

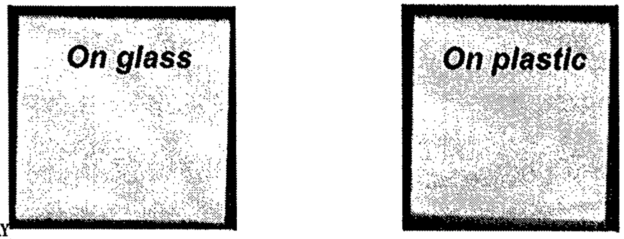


TOLEDs with and without a Cover Glass



Flexible OLEDs (FOLEDs)



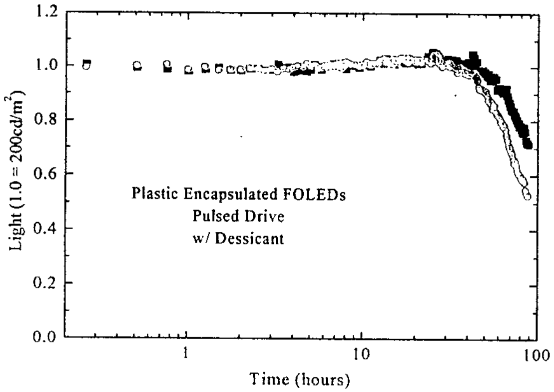


Key FOLED Issues

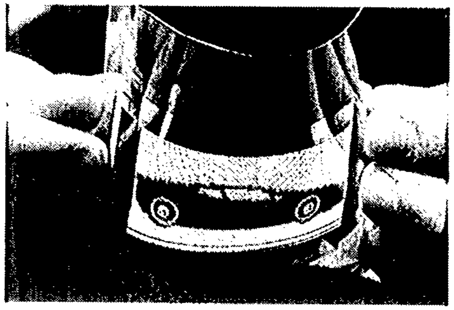
- Packaging
  - Permeability/OLED lifetime
  - Conformability, flexibility
  - Press durability
- Yield
  - Substrate processibility
  - Temperature and chemical resistance, surface roughness
  - ITO performance and patternability
- Display Fabrication
  - Passive/active matrix architecture
  - Module assembly

Plastic Encapsulated FOLED

Plastic with No Barrier Coating



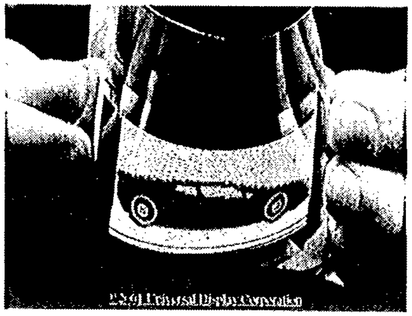
Flexible Display Prototypes



Passive Matrix Built on ITO/Plastic

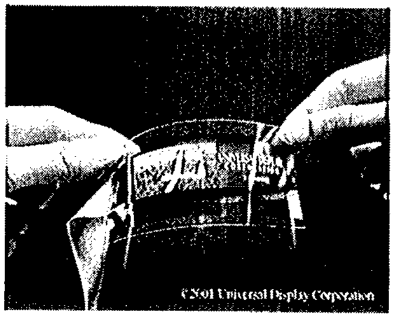
Passive Matrix Built on Battelle Barrier Coated Plastic

Flexible Display Progress



2000

- 64 x 128 passive matrix display
- 60 dpi resolution
- 60 Hz refresh rate
- 0.175 mm PET substrate

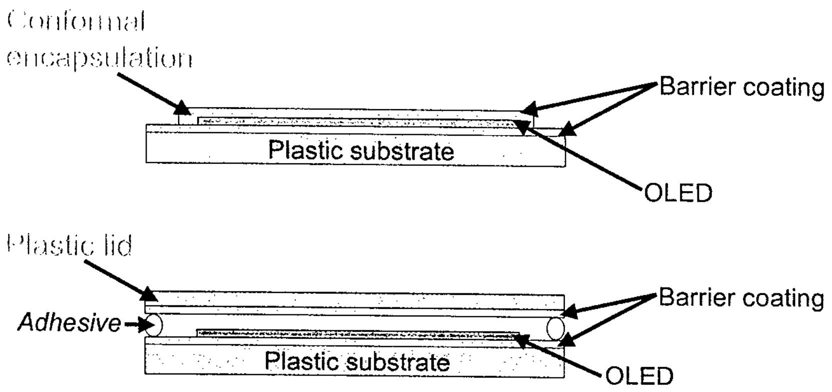


2001

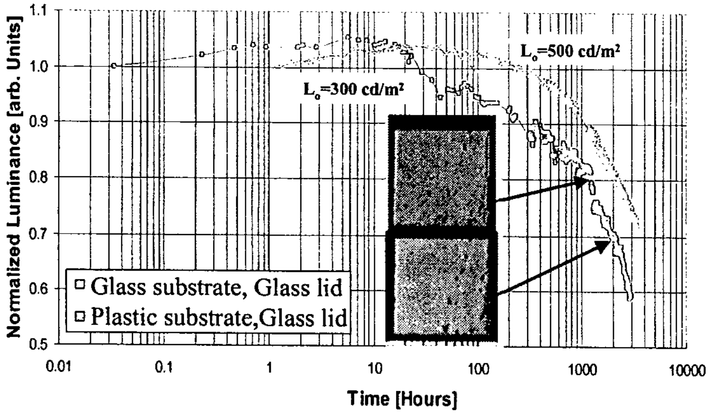
- 64 x 240 passive matrix display
- 80 dpi resolution
- 120 Hz refresh rate
- 0.175 mm PET substrate
- full motion video

U.S. Patent No. 5,844,363

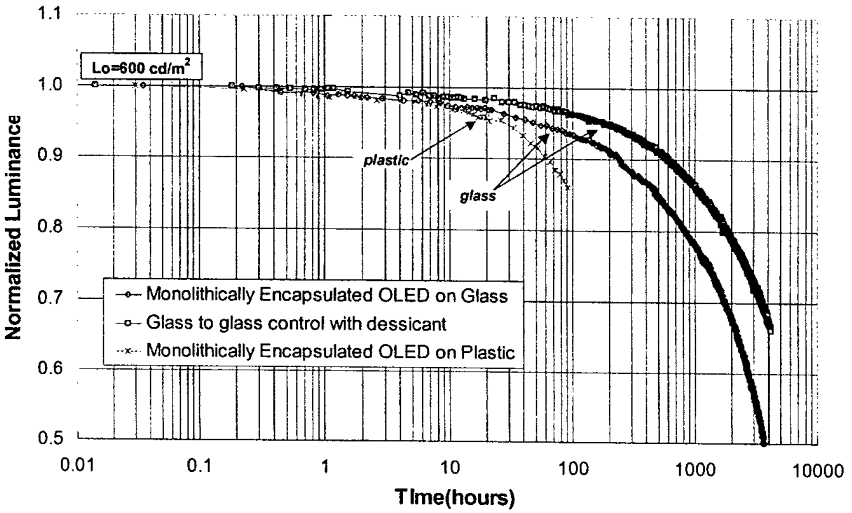
Flexible Packaging Options



Lifetime of OLEDs on Plastic vs. Glass

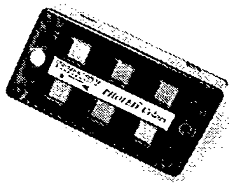


Evaluation of Monolithic Encapsulation



Phosphorescent OLED Performance

EL color	Deep red	Red	Blue	Green
Peak wavelength (nm)	650	620	474	514
CIE - x	0.71	0.65	0.16	0.30
CIE - y	0.29	0.35	0.37	0.63
Luminance eff @ 1 mA/cm^2 (cd/A)	1.0	11	13	24
Lifetime (hours)	100,000 @ 70 cd/m^2	>7,000 @ 300 cd/m^2	under development	>8,000 @ 500 cd/m^2



Other Key Accomplishments Since 1997

- Transparent/Top Emission TOLEDs
  - Efficiency as high as Bottom Emission
  - Lifetime > 3,000 hours
- Flexible OLEDs
  - Process Yield Understood
  - Demonstrated World's First FOLED Display
  - On our way to enhancing lifetime

What directions are we headed?

- in the areas from the HDS legacy -

- Reliability
  - Developing Epoxyless Packages
  - Developing New Materials and Improved Architectures
  - Maximizing the Efficiency x Lifetime Product
  - Investigating High Temperature Operation
- Prototypes
  - Flexible Displays
  - AMOLED Prototypes with Partners
  - Transparent Displays
- Pilot Line…. I.e. building the business

The Business

TECHNOLOGY DEVELOPMENT

- *Cutting-edge research & development*
- *Expanding intellectual property portfolio*
- *Process development & product prototyping*

TECHNOLOGY TRANSFER

- *Patents, know-how and training*
- *High-purity organic materials*
- *Next-generation OLED deposition equipment*

COMMERCIALIZATION PARTNERSHIPS

- *Co-development programs*
- *Licensing*
- *Joint ventures*

USC UNIVERSITY OF SOUTHERN CALIFORNIA

PPG

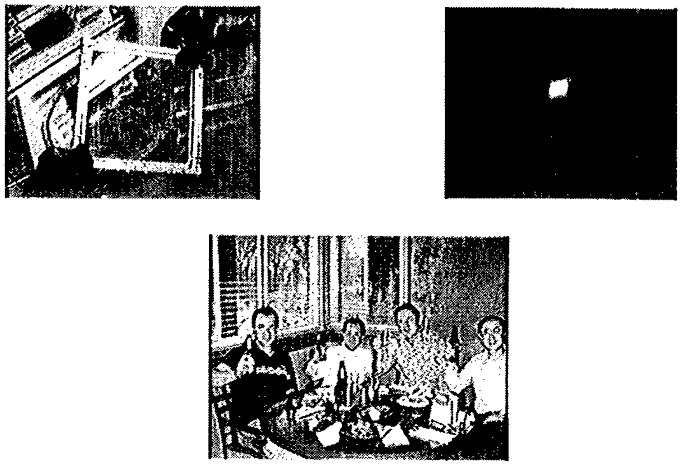
AIXTRON The CVD Engineering Company

LUXELL

SONY

SAMSUNG SDI

First OLED on OVPD Pilot Line System



Thanks for your support!

Thanks to the Entire Teams of UDC, Princeton University and University of Southern California for an Awesome Collaboration