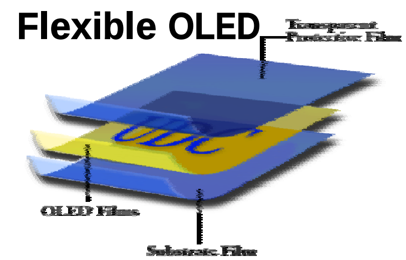
Lecture 7
6.976 Flat Panel Display Devices

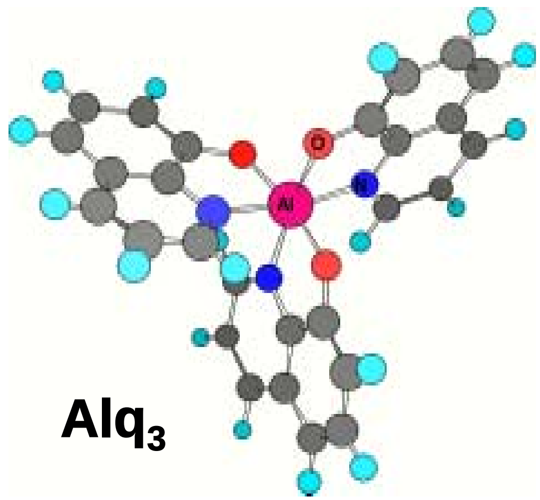
Emissive Displays -
Organic Electroluminescence

- types of organic materials
- growth of organic materials
- organic light emitting devices
- OLED-based displays



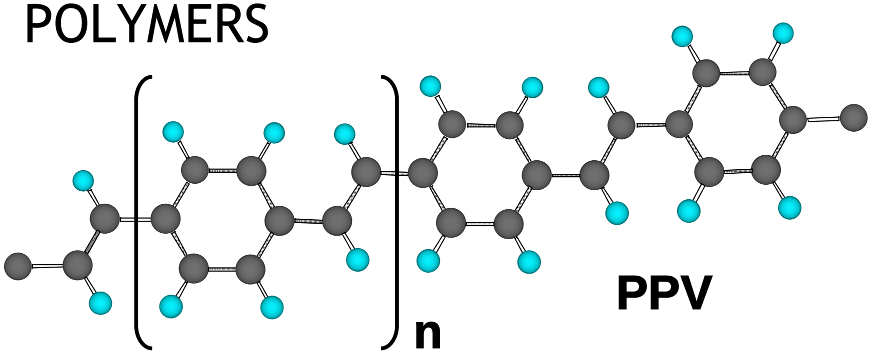
Organic Materials

MOLECULAR MATERIALS



Alq_3

POLYMERS



PPV

Attractive due to:

- Integrability with inorganic semiconductors
- Low cost **(fabric dyes, biologically derived materials)**
- Large area bulk processing possible
- Tailor molecules for specific electronic or optical properties
- Unusual properties not easily attainable with conventional materials

But problems exist:

- Stability
- Patterning
- Thickness control of polymers
- Low carrier mobility

Scientific Interest in Organic Materials

- 1828 - Wöhler first synthesized urea
  without the assistance of a living organism
- 1950's - steady work on crystalline organics starts
- 1970's - organic photoconductors (xerography)
- 1980's - organic non-linear optical materials
- 1987 - Kodak group published the first
  efficient organic light emitting device (OLED)
- Since then, the field has dramatically expanded
  both commercially and scientifically
  (OLEDs, transistors, solar cells, lasers, modulators, ...)

to date, about two million organic compounds have been made
- this constitutes nearly 90% of all known materials -

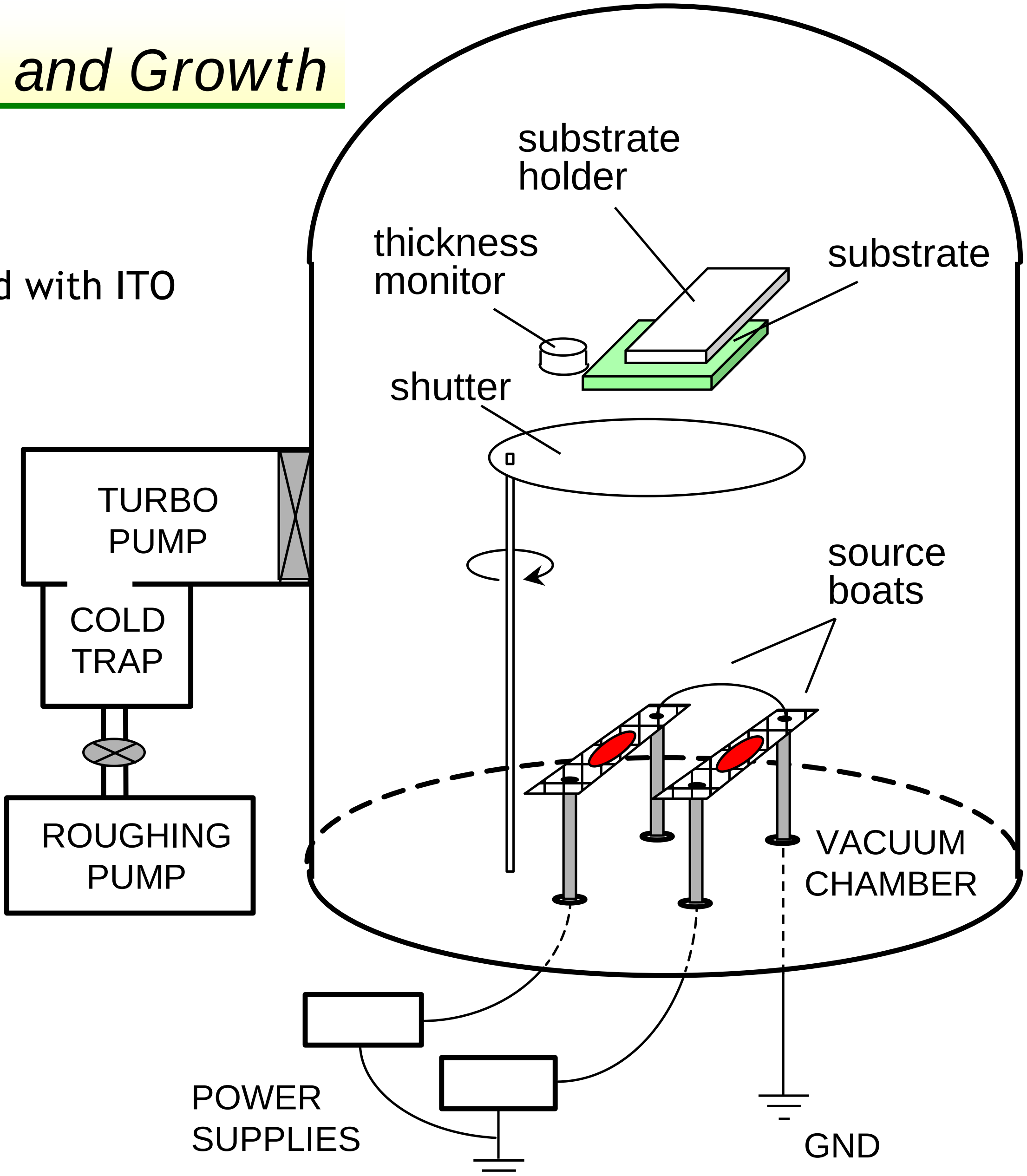
Device Preparation and Growth

- Glass substrates precoated with ITO
  - 94% transparent
  - 15 Ω/square

- Precleaning
  Tergitol, TCE
  Acetone, 2-Propanol

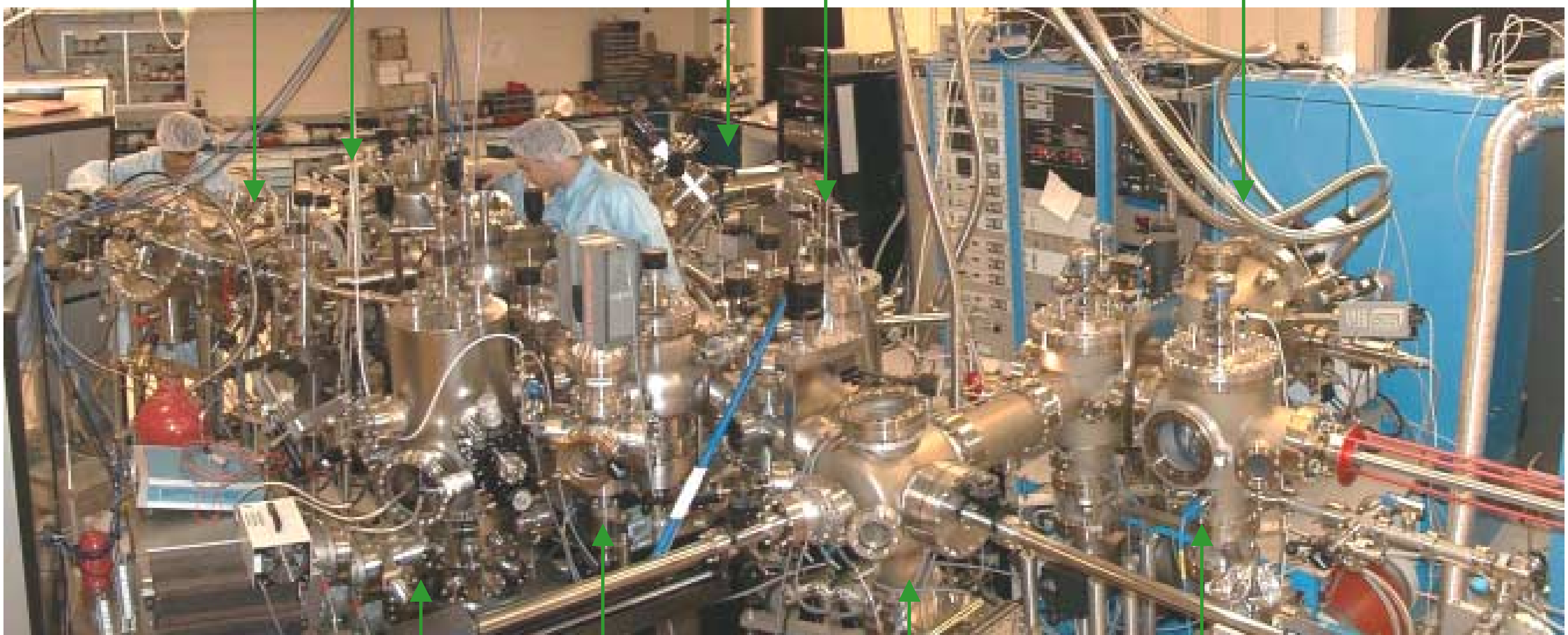
- Growth
  - 5 x 10^{-7} Torr
  - Room T

  - 20 to 2000 Å layer thickness



Materials Growth Laboratory

Base Pressure 10^{-9} ~ 10^{-11} torr



Princeton University

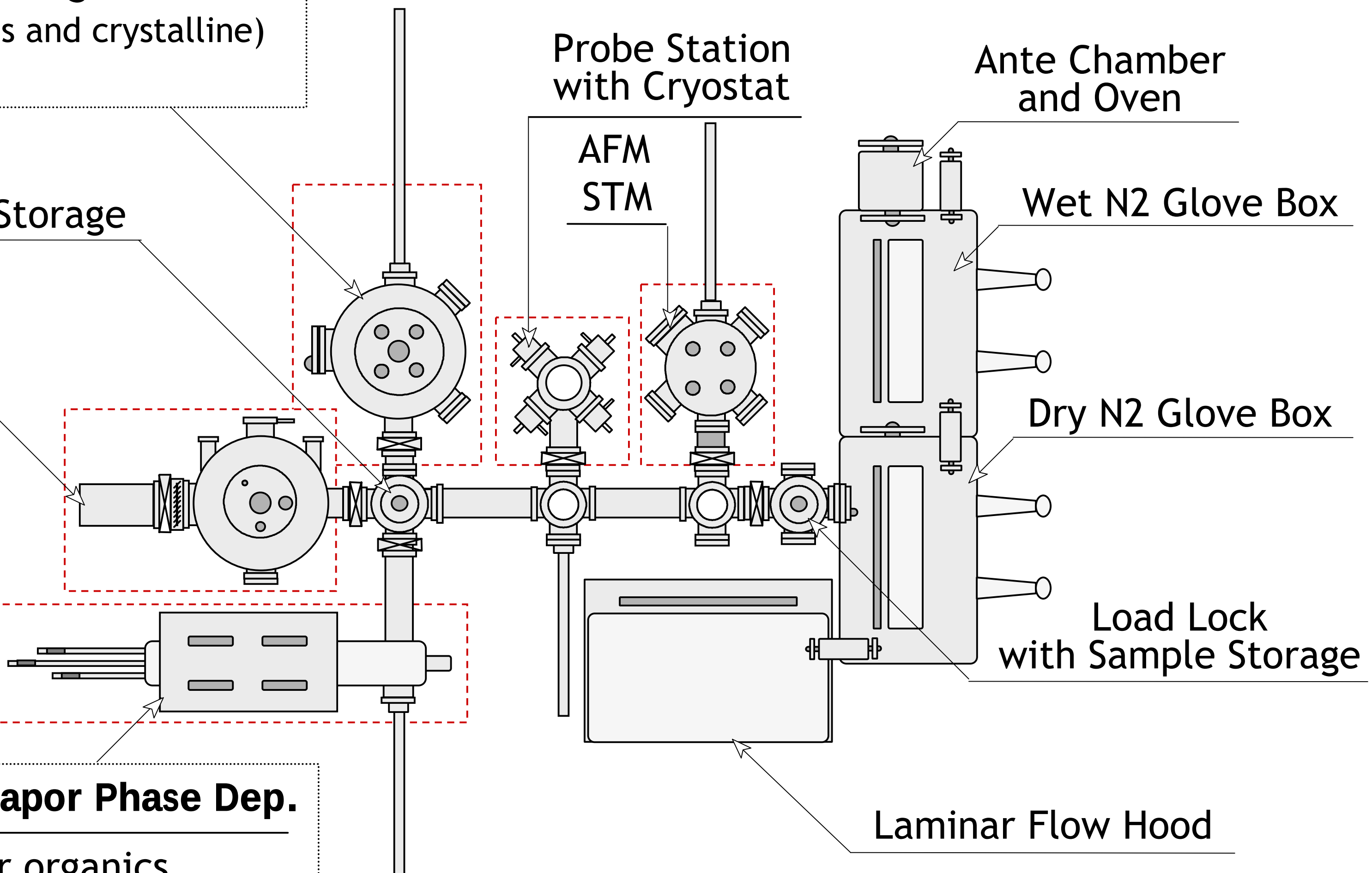
Integrated Materials Growth System

Evaporative Deposition

- molecular organics
  (amorphous and crystalline)
- metals

Sputtering

- ITO
- ceramics

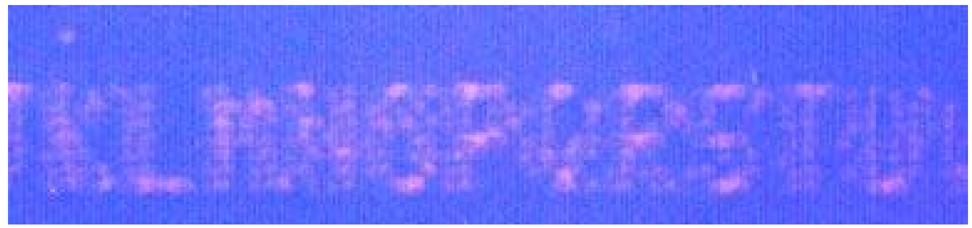


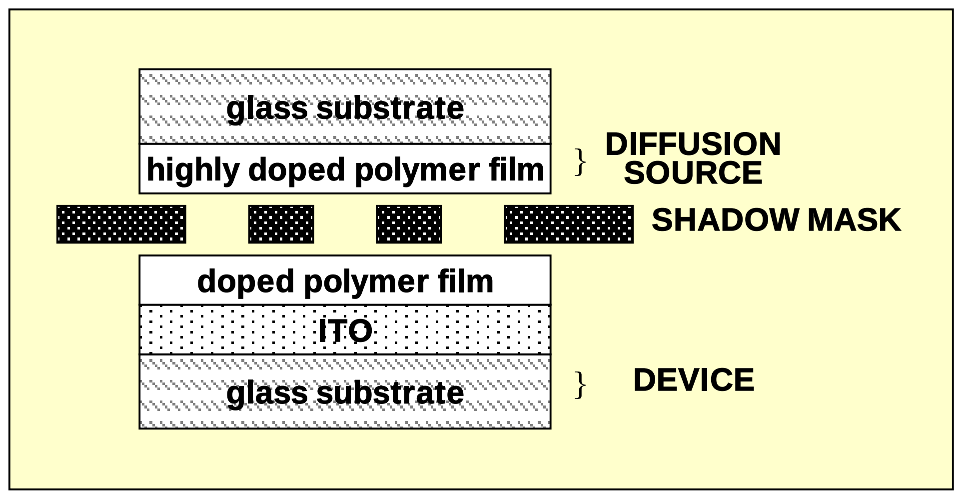
Physical & Vapor Phase Dep.

- molecular organics
- nano-dots **
- solvated polymers **
- colloids **

Other Growth Methods

- Spin-on
- Langmuir-Blodgett
- Inkjet Printing
- Dye Diffusion
- Silkscreen





Development of Organic LEDs

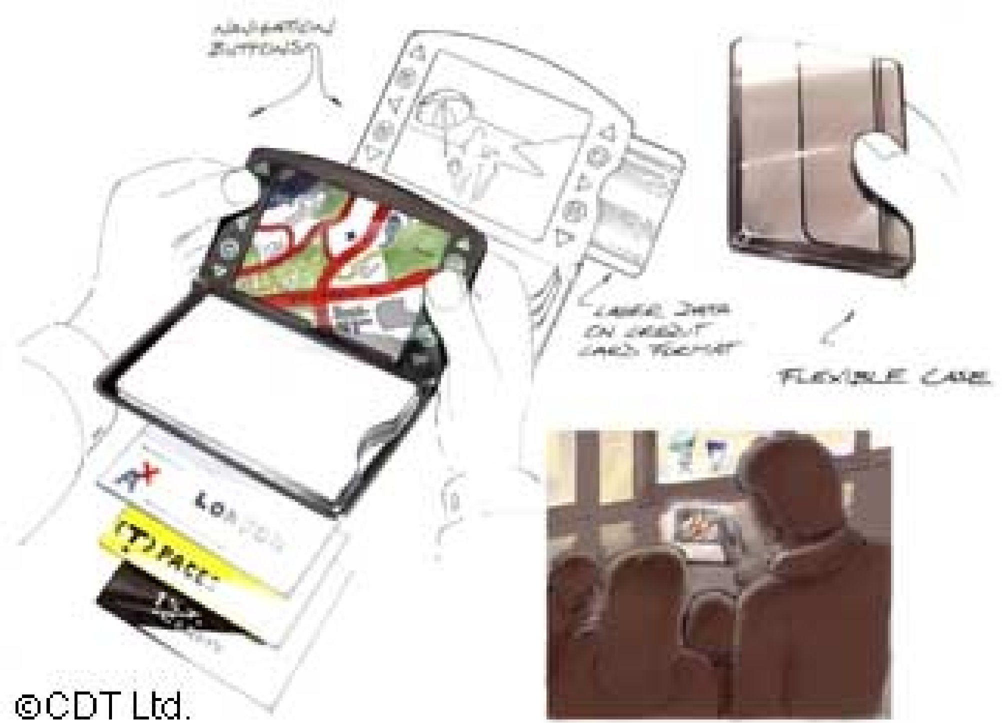
- Conventional, Transparent, Inverted, Metal-Free, Flexible, Stacked

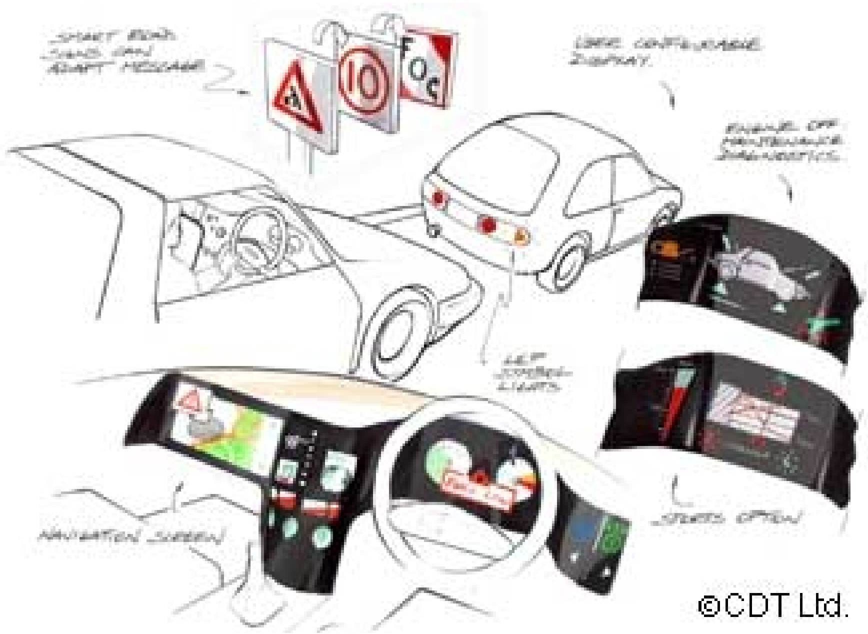
~ OLED, TOLED, OILED, MF-TOLED, FOLED, SOLED ~

- Displays

Personal Organizer, Notebook

Rugged, high resolution, full-color, video-rate displays



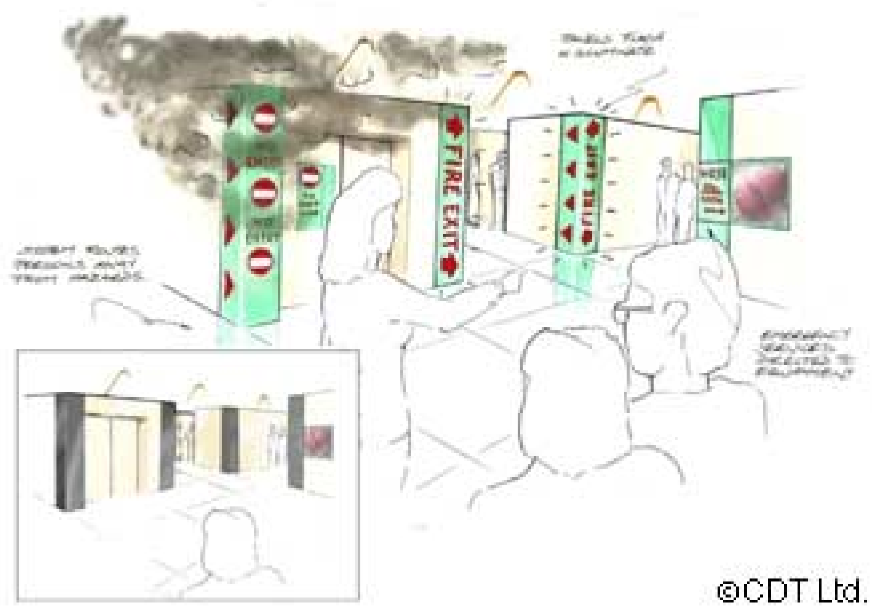


Automotive

Dashboard displays, external indicator lights, and road signs

Multi-Function Video Watch

Rugged, high resolution, full-color, video-rate displays enable a multitude of applications



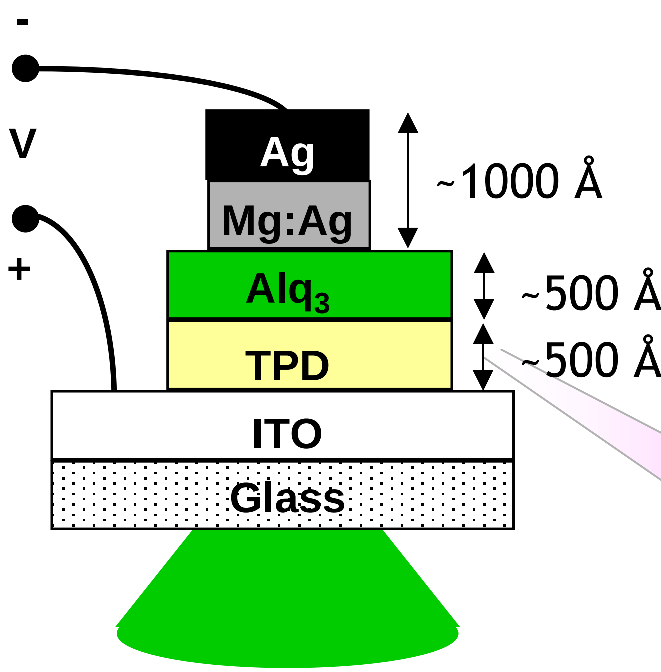
Active Wallpaper

Large area displays

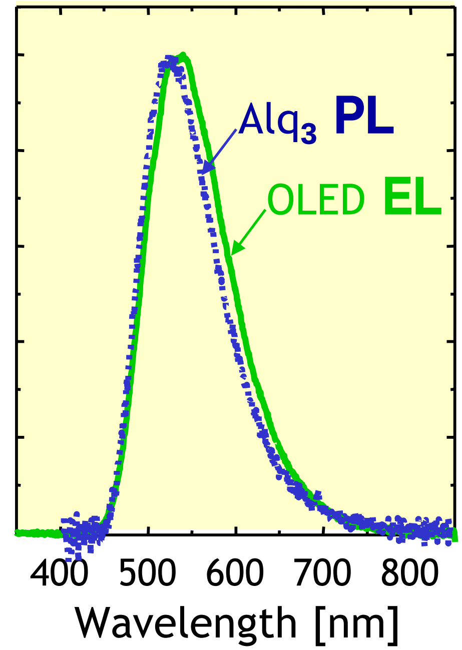
Active Clothing

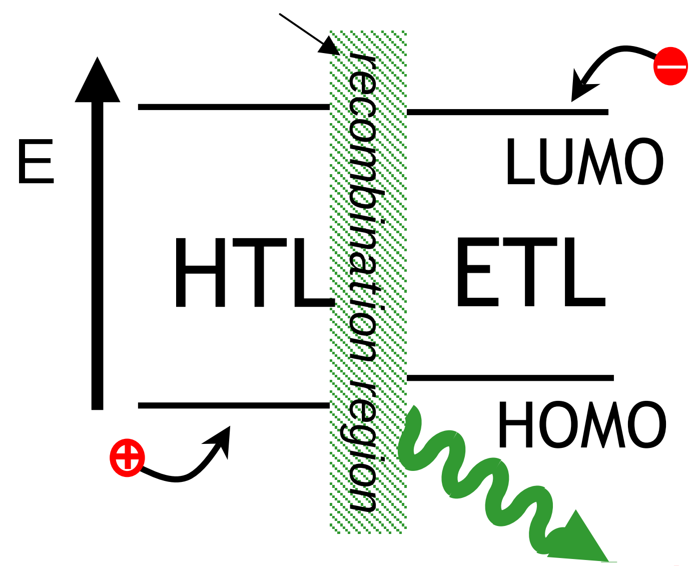
Light, rugged, low voltage, flexible displays

Why do OLEDs Glow ?

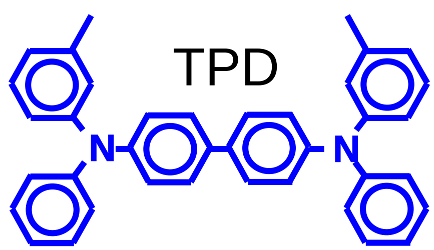


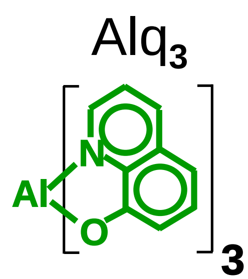
electrons and holes form ***excitons*** (bound e^--h^+ pairs)



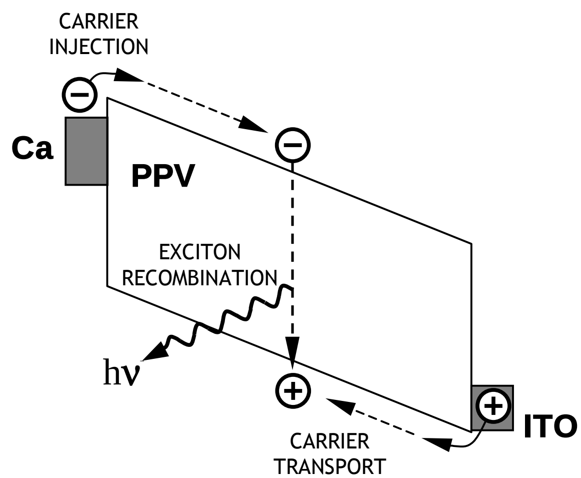


some excitons radiate

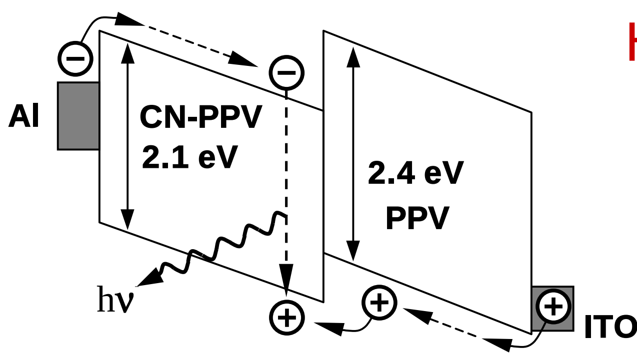




Electroluminescence

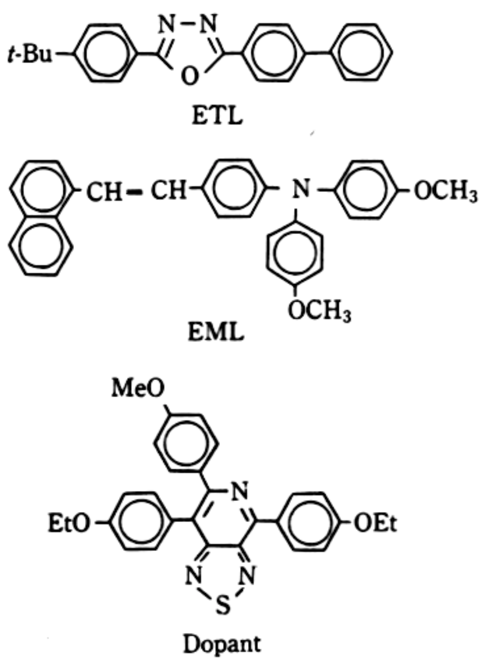


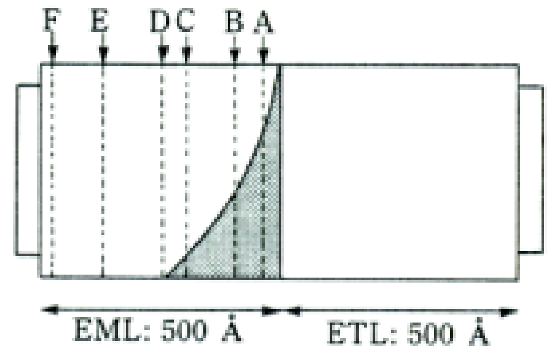
Single Layer Device

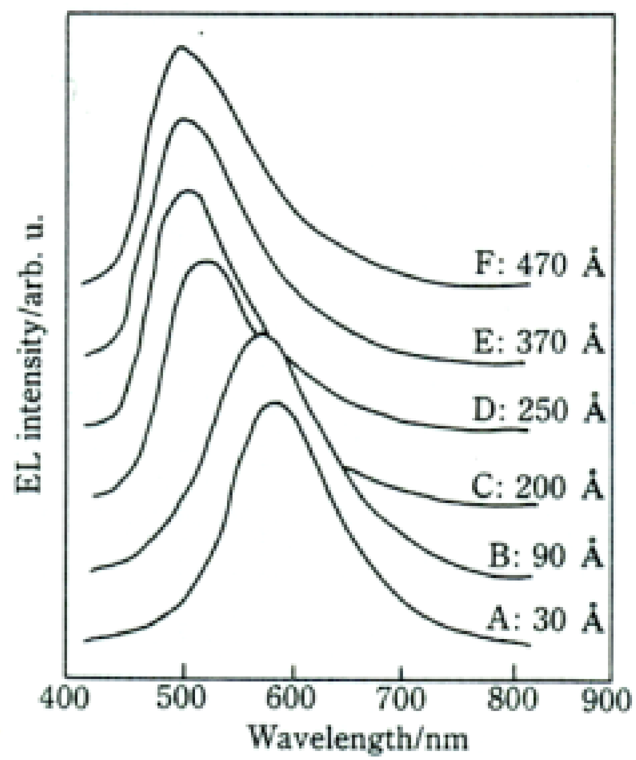


Heterostructure Device

Exciton Recombination Zone



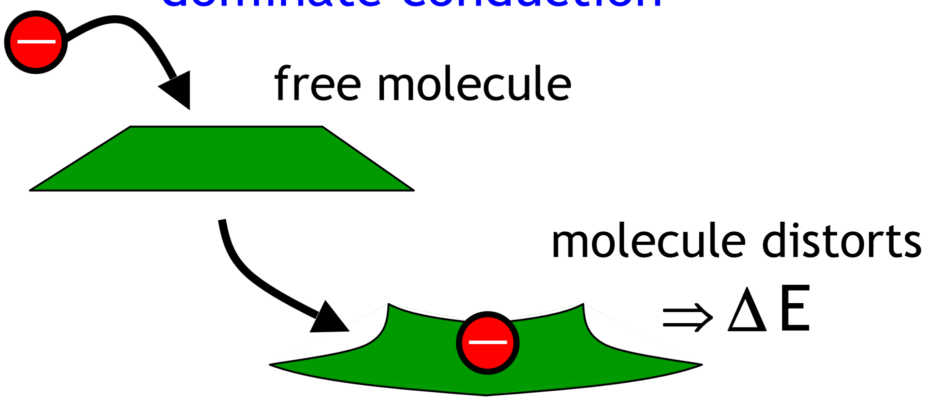


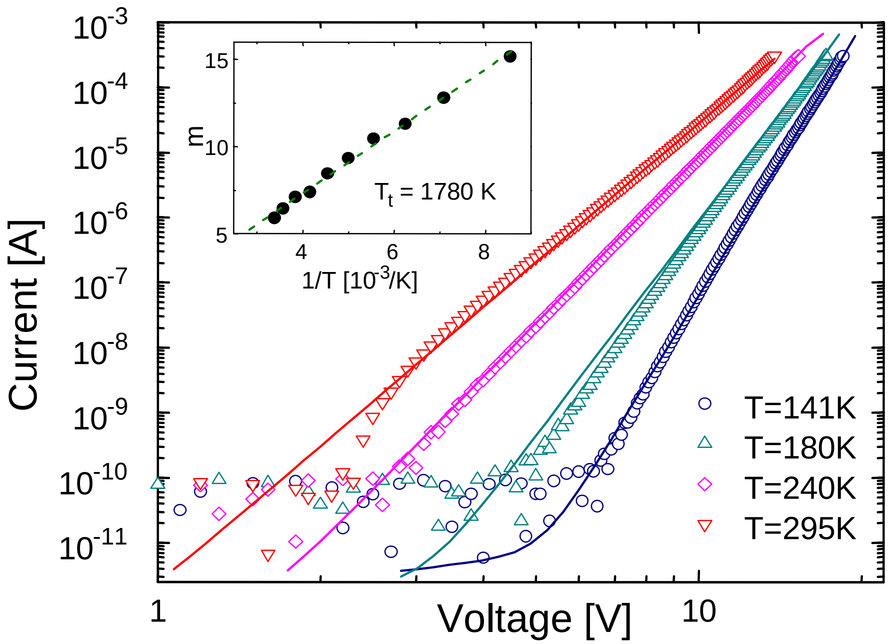


C. Adachi, *et al.*

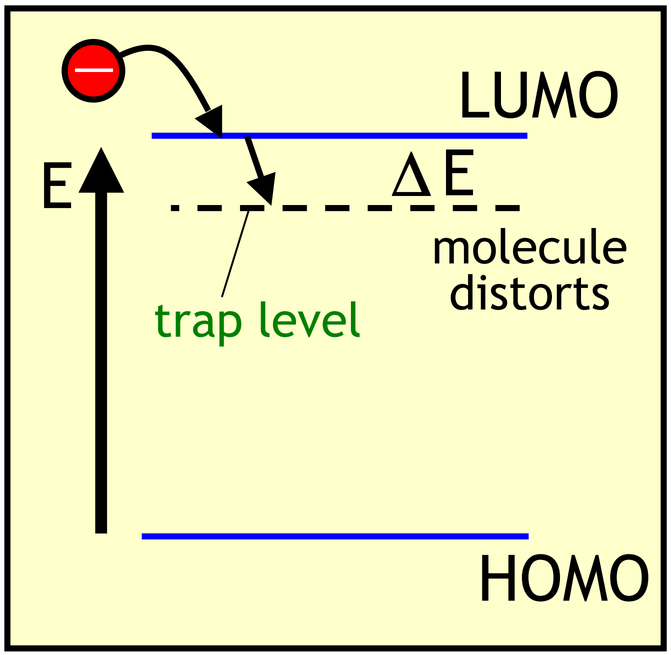
Trap Limited Conduction in Organic Materials

charge trapping can dominate conduction





Shen, Burrows, Bulović, McCarty, Thompson, Forrest, *Jpn. J. Appl. Phys.* 35, L401 (1996).

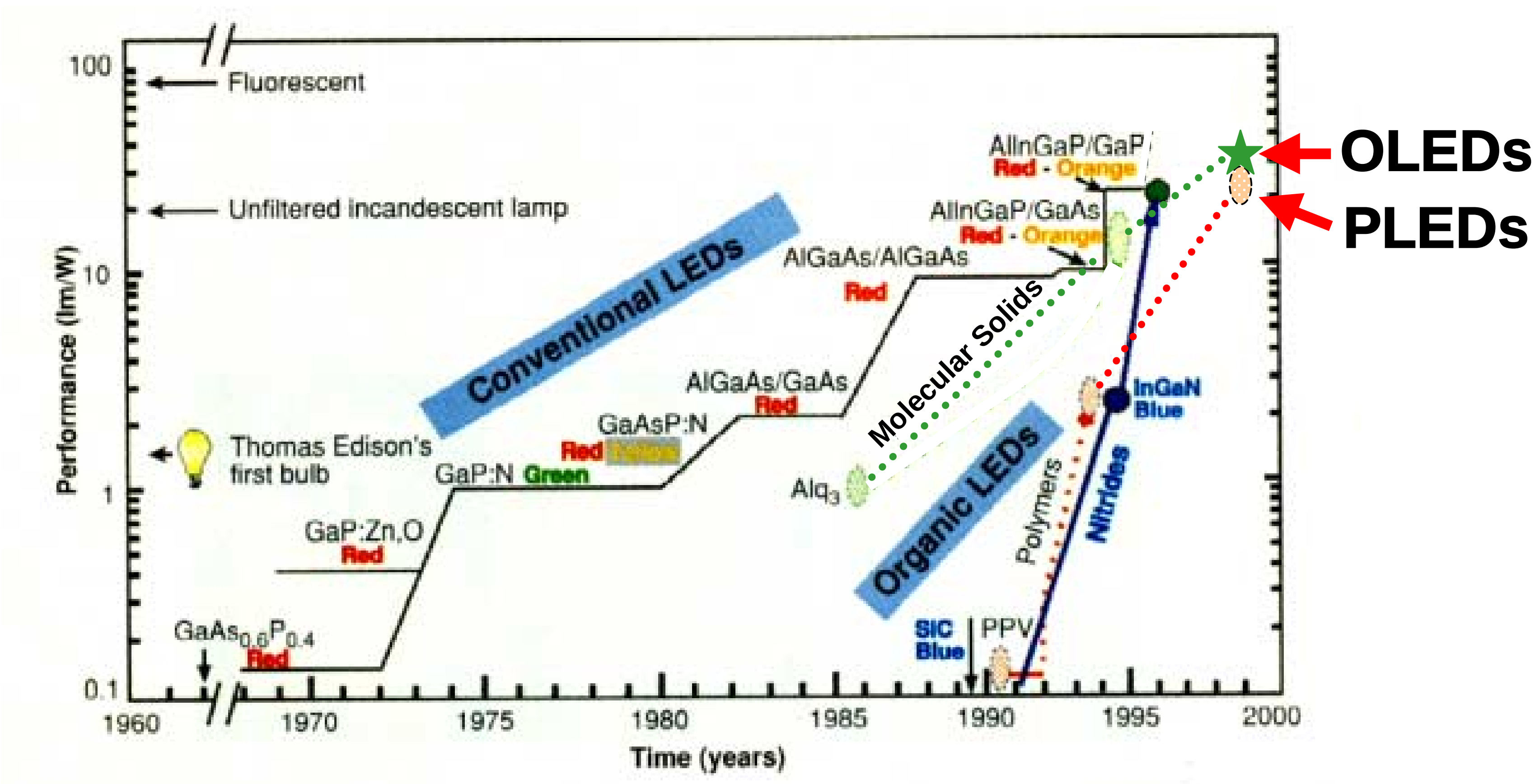


$$J \propto N_{LUMO}\,\mu_n N_t^{\,m} d^{-2m-1} V^{m+1}$$

$$m = T_t/T$$

$N_t = 3.1\times10^{18}\,cm^{-3}$,
$\mu_n N_{LUMO} = 4.8\times10^{14}$/cm-V-s

Progress in LED Efficiency



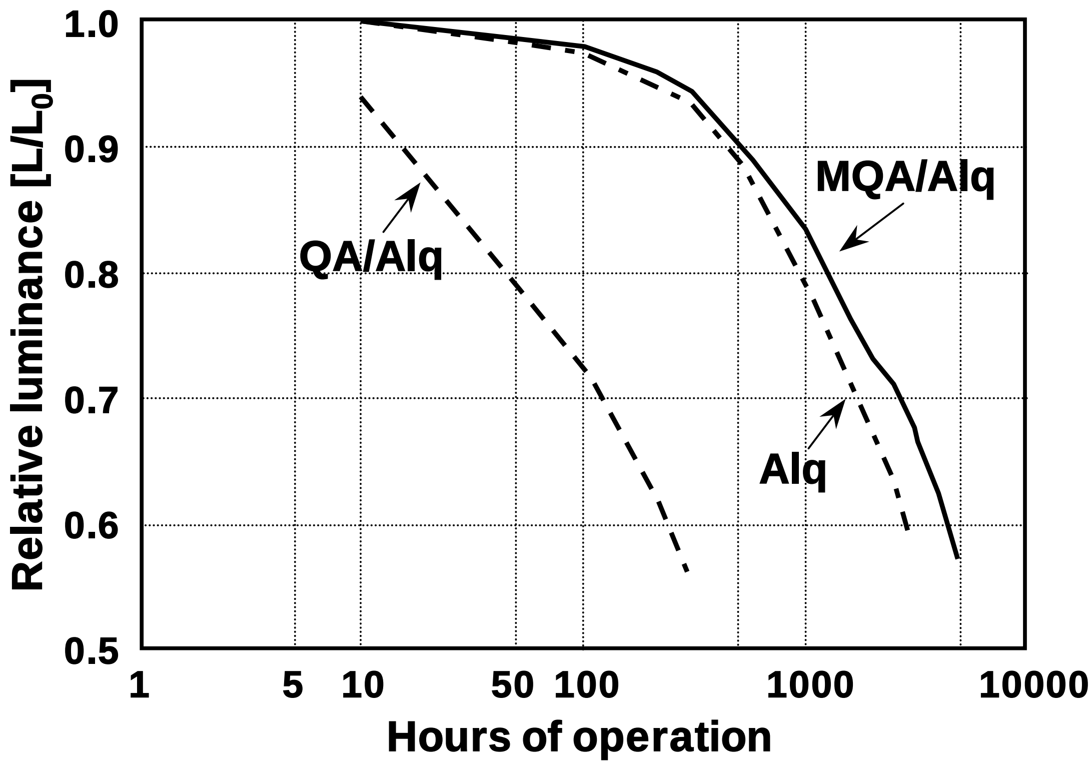
after Sheats *et al.*, *Science* 273, 884 (1996).

Why Make Organic LEDs

WE DEMONSTRATED OLEDS THAT ARE :

- Bright - 100,000 cd/m2 (30,000 ft-L)
- Efficient - >30 lm/W
- Scalable Emissive Area - from a few μm to a few cm in size
- Colors - fluorescent R,G,B and phosphorescent R,G
- Low Voltage - 3 to 10 V
- Low Cost Materials
- Low Cost Substrates
- Wide Viewing Angle - >160 deg
- Reliability - 1,000,000 hrs (phosphorescent R half-life)

OLED Stability

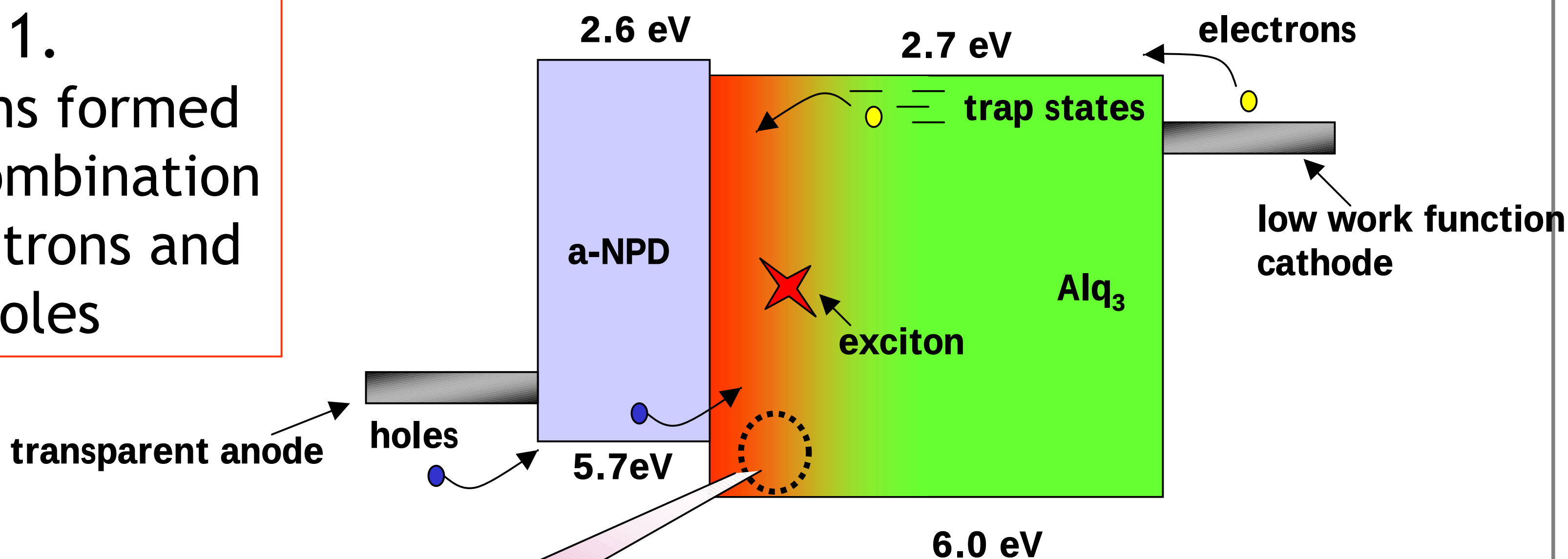


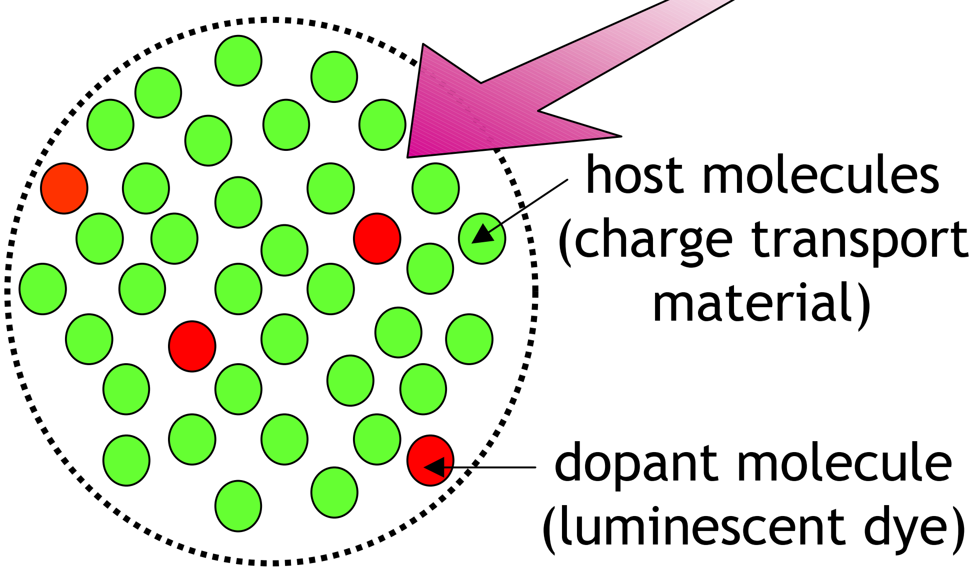
Alq_3 devices driven at 20 mA/cm^2

Initial luminance for Alq_3 is 510 cd/m^2
for QA doped Alq_3 devices is 1600 cd/m^2
and for MQA doped Alq_3 devices is 1400 cd/m^2 (C.W. Tang)

Electroluminescence in Doped Organic Films

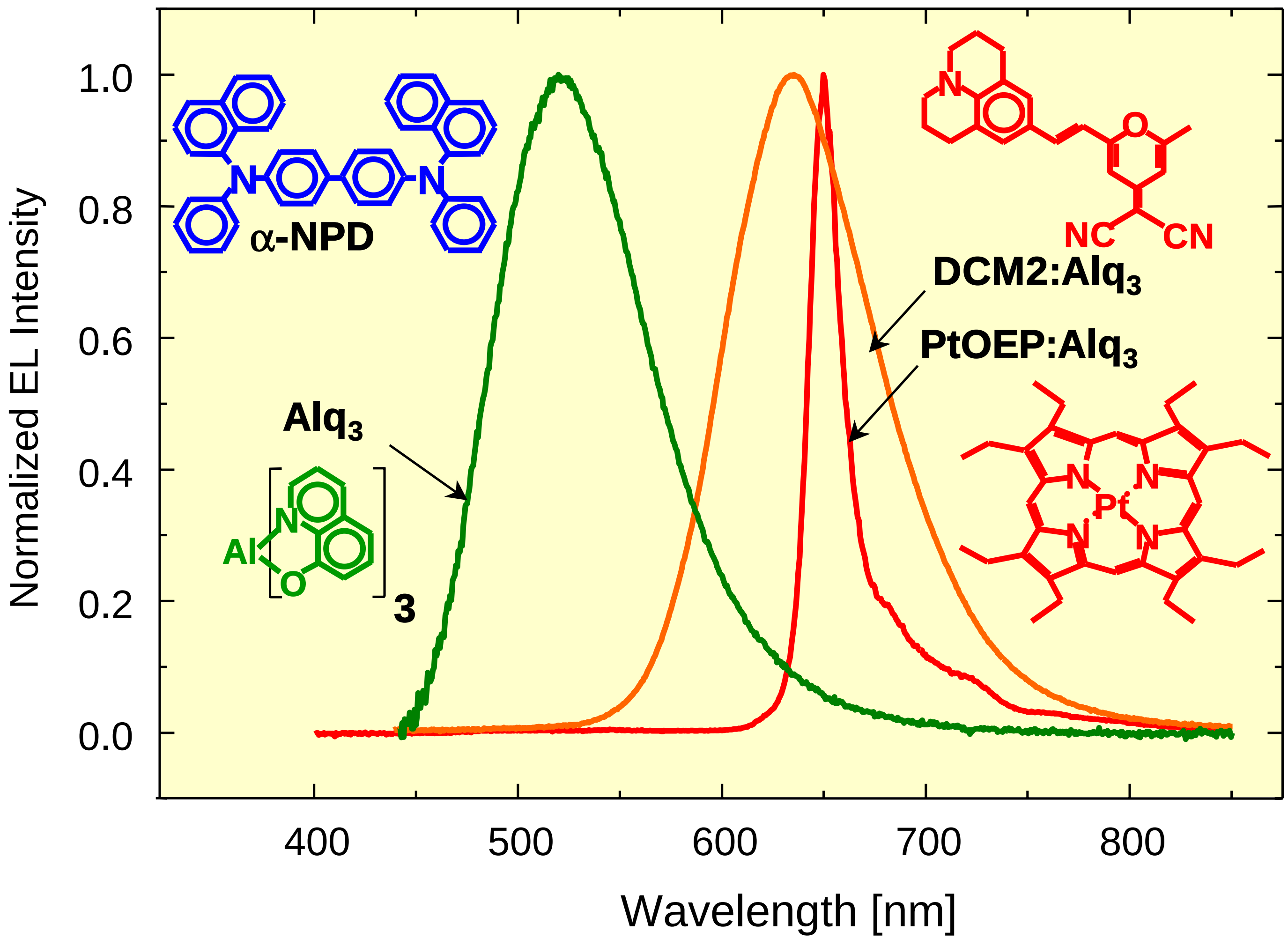
1.
Excitons formed from combination of electrons and holes





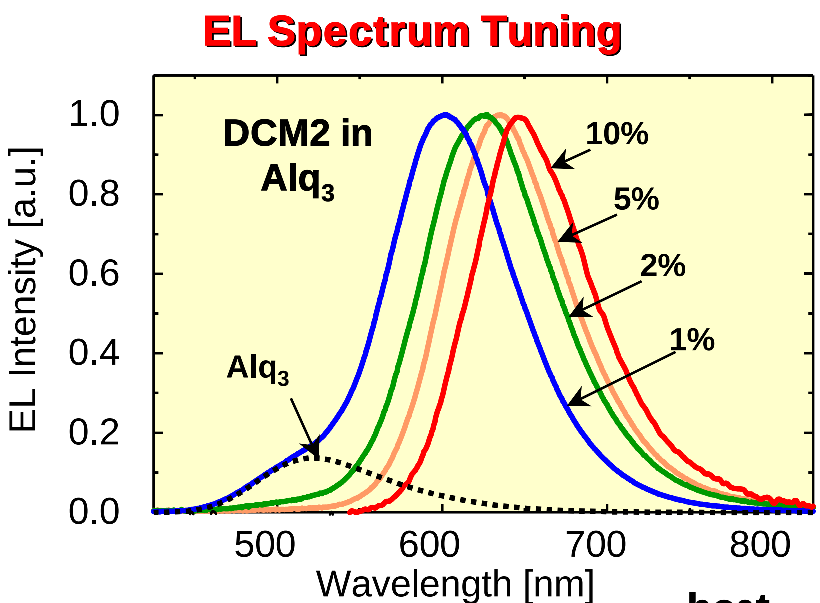
2.
Excitons transfer to luminescent dye

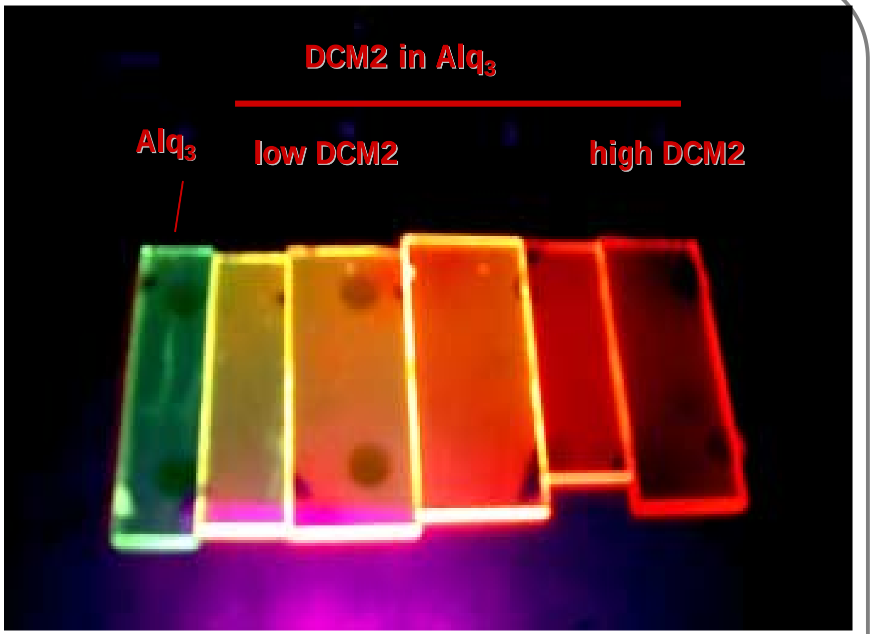
Effect of Dopants on the OLED EL Spectrum

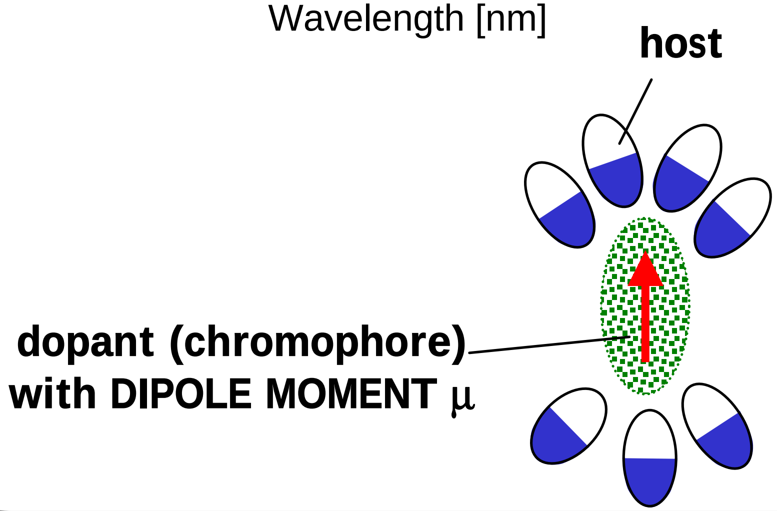


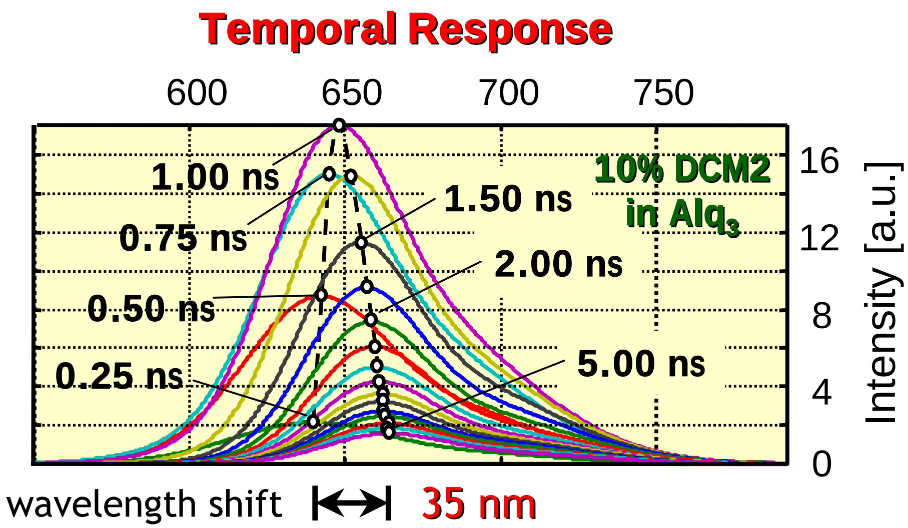
Solid State Solvation Effect

Bulović *et al.*, *Chem. Phys. Lett.* 287, 455 (1998); 308, 317 (1999).

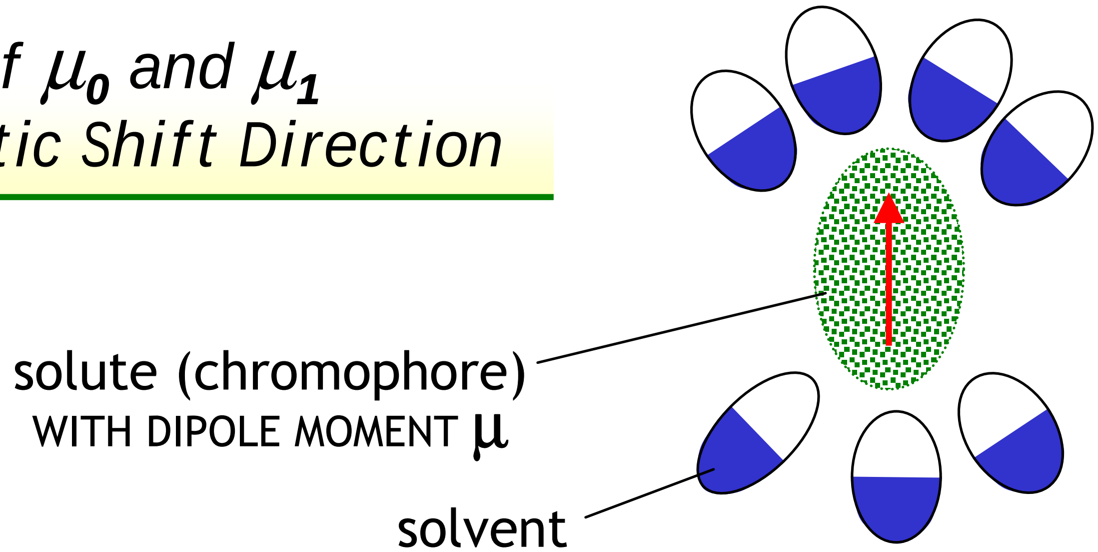


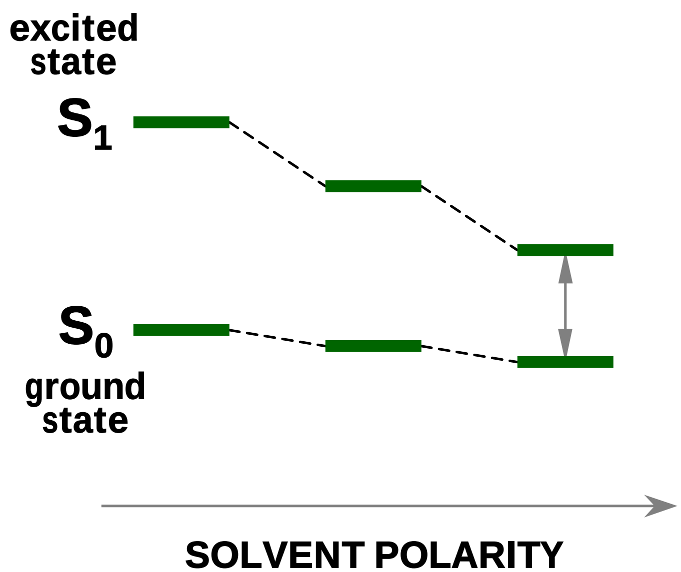




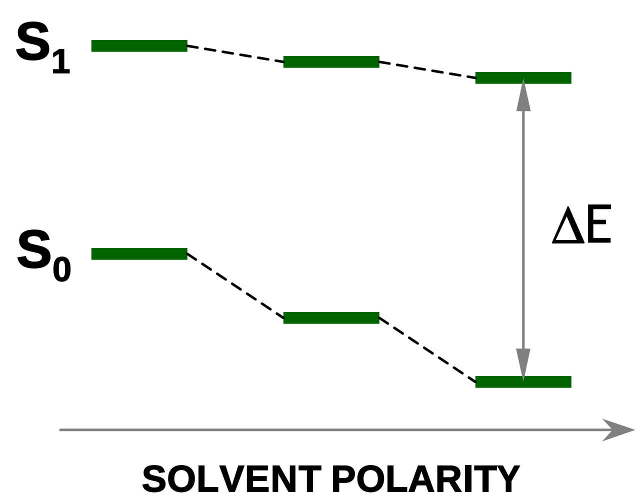


Influence of μ_0 and μ_1 on Chromatic Shift Direction



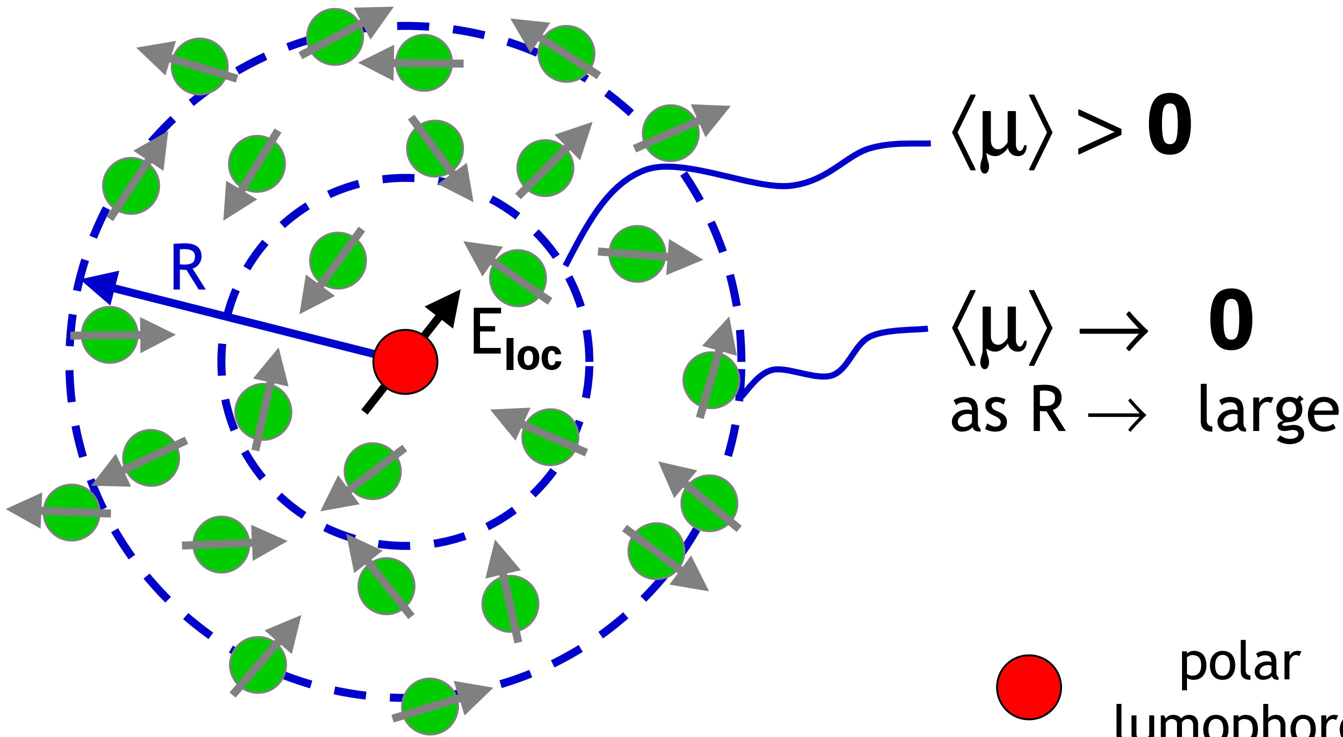


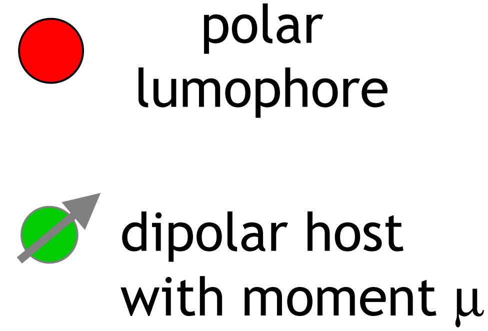
$\mu_0 < \mu_1$



$\mu_0 > \mu_1$

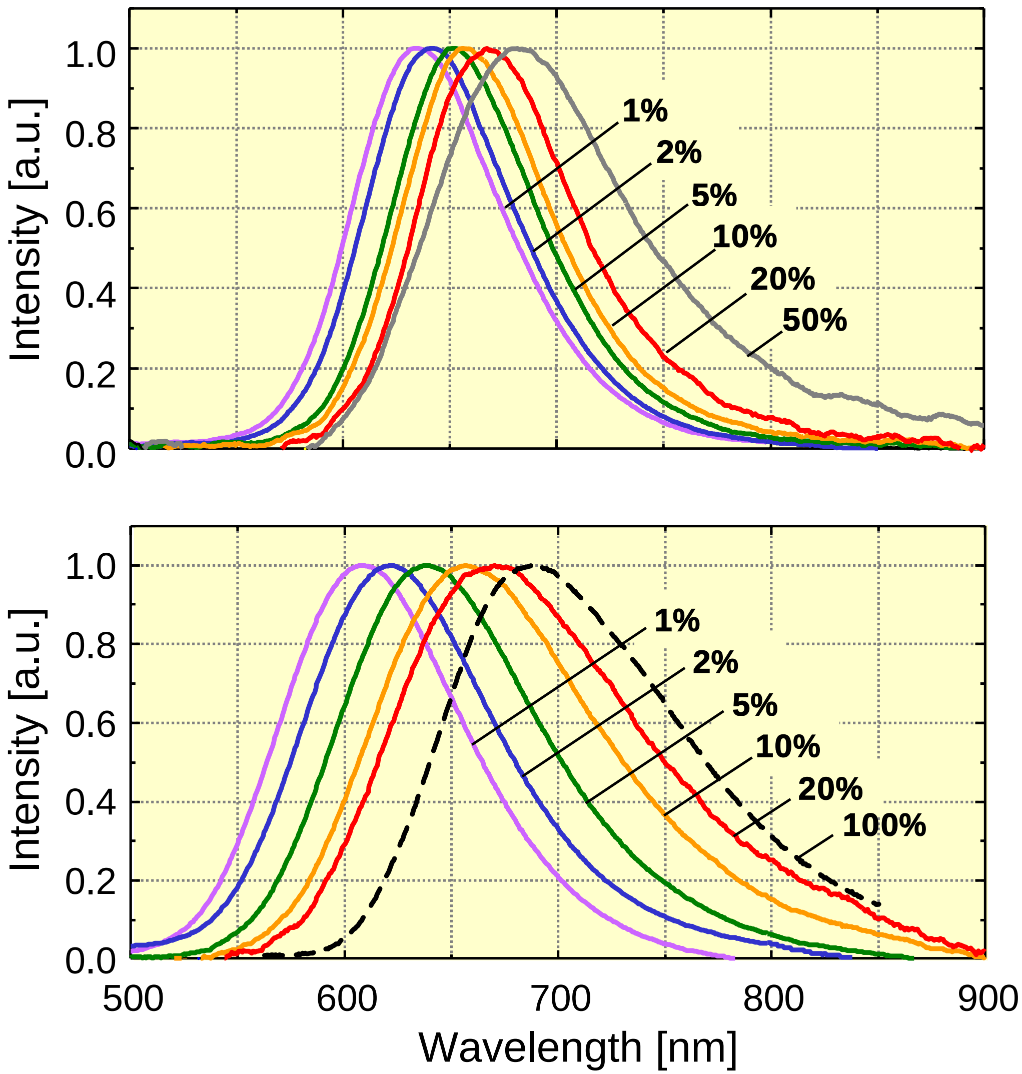
Solid State Solvation Effect (SSSE)





"self polarization"
for strongly dipolar lumophores

Thin Film Photoluminescence



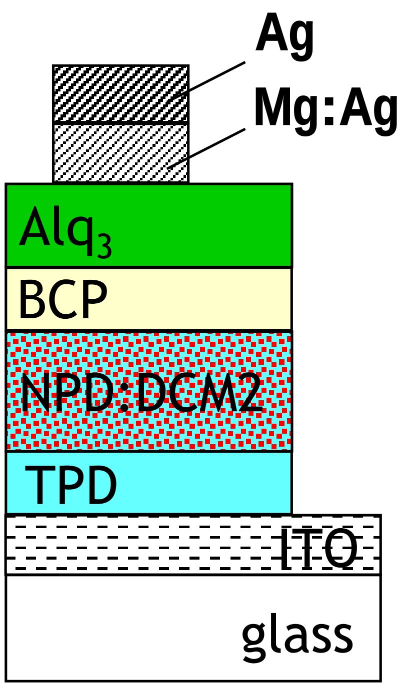
DCM2 in Alq_3

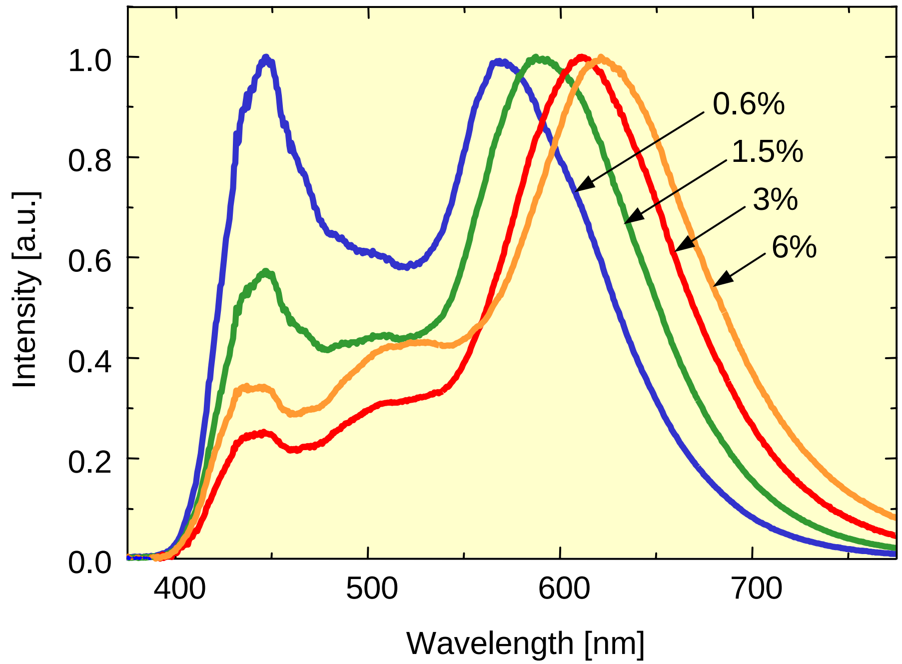
polar host
μ ~ 5.5 D

DCM2 in Zrq_4

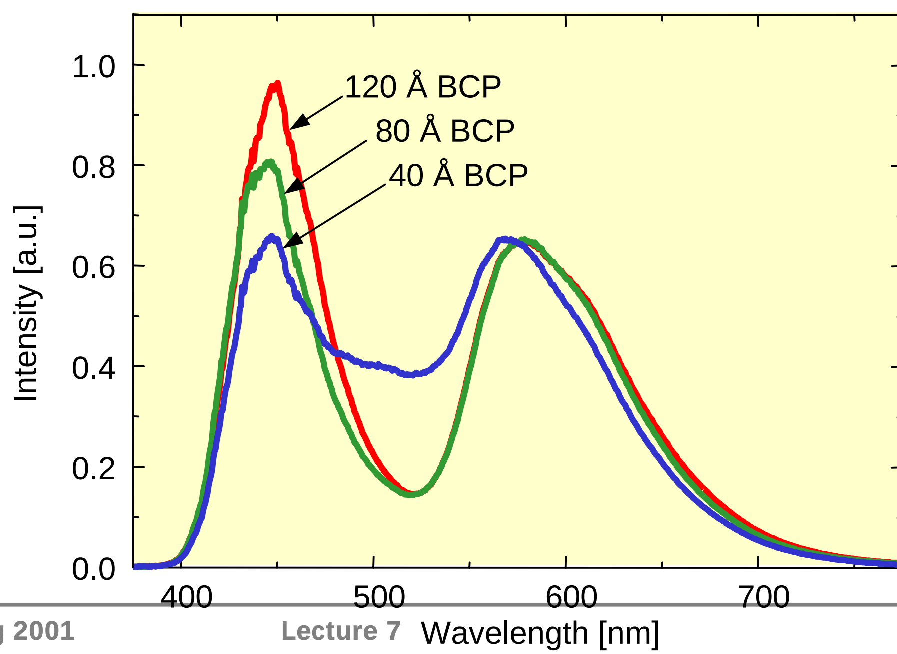
non-polar host

Tuning Emission of White OLEDs



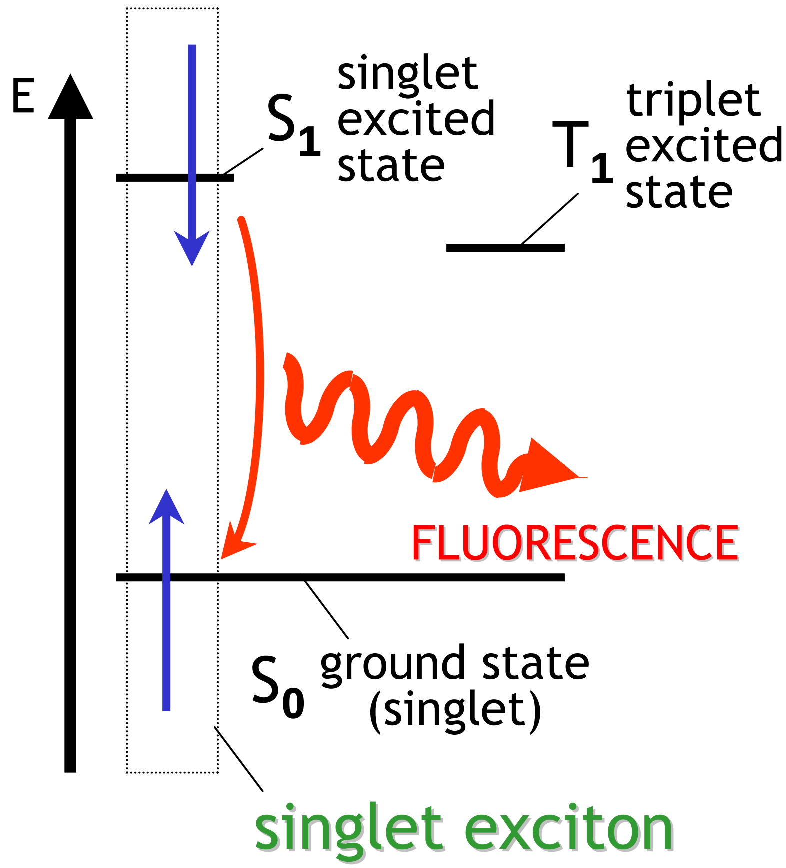


changing DCM2 in α-NPD concentration (with 40A BCP)



changing BCP layer thickness (with 0.6% DCM2)

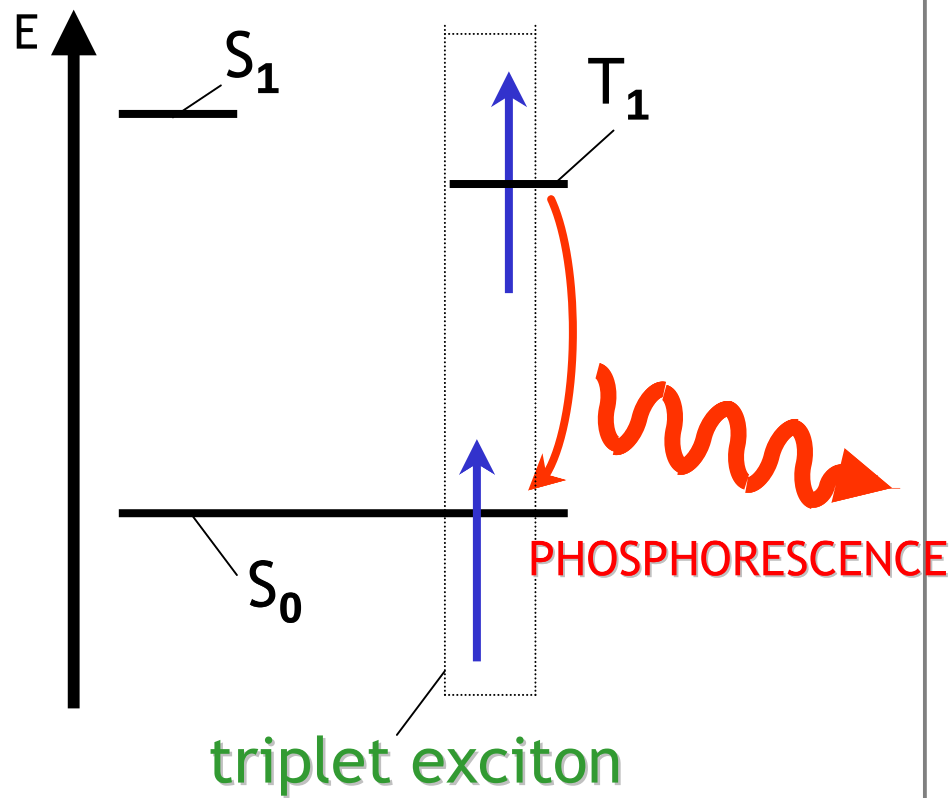
Fluorescence



- symmetry conserved

fast process ~10^{-9}s

Phosphorescence



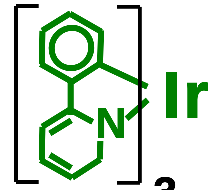
- triplet to ground state transition is not permitted

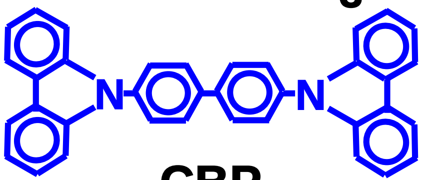
slow process ~ 1s

Phosphorescent OLED Performance

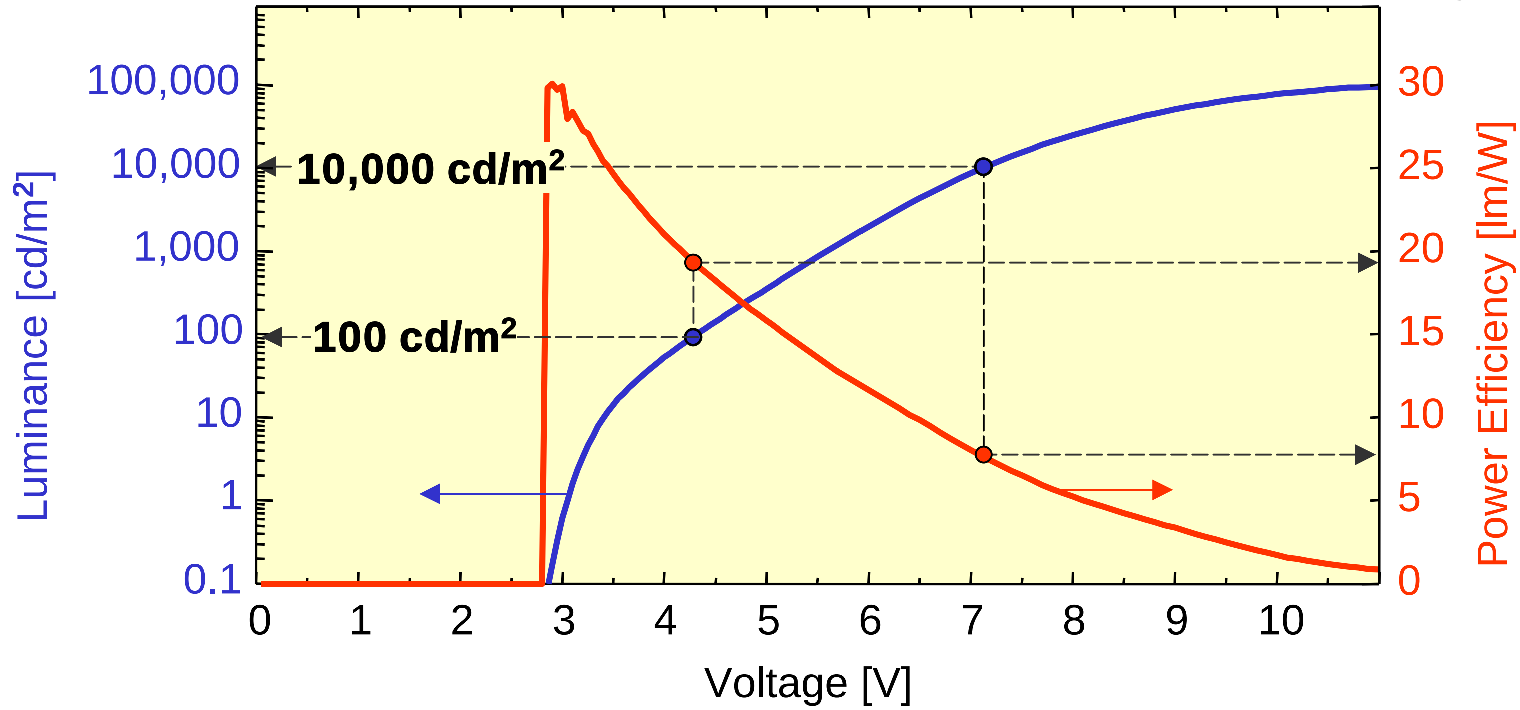
6% Ir(ppy)$_3$ in CBP OLED:

at 100 cd/m^2 : 4.5 V, 19 lm/W
at 10,000 cd/m^2 : 7.2 V, 8 lm/W





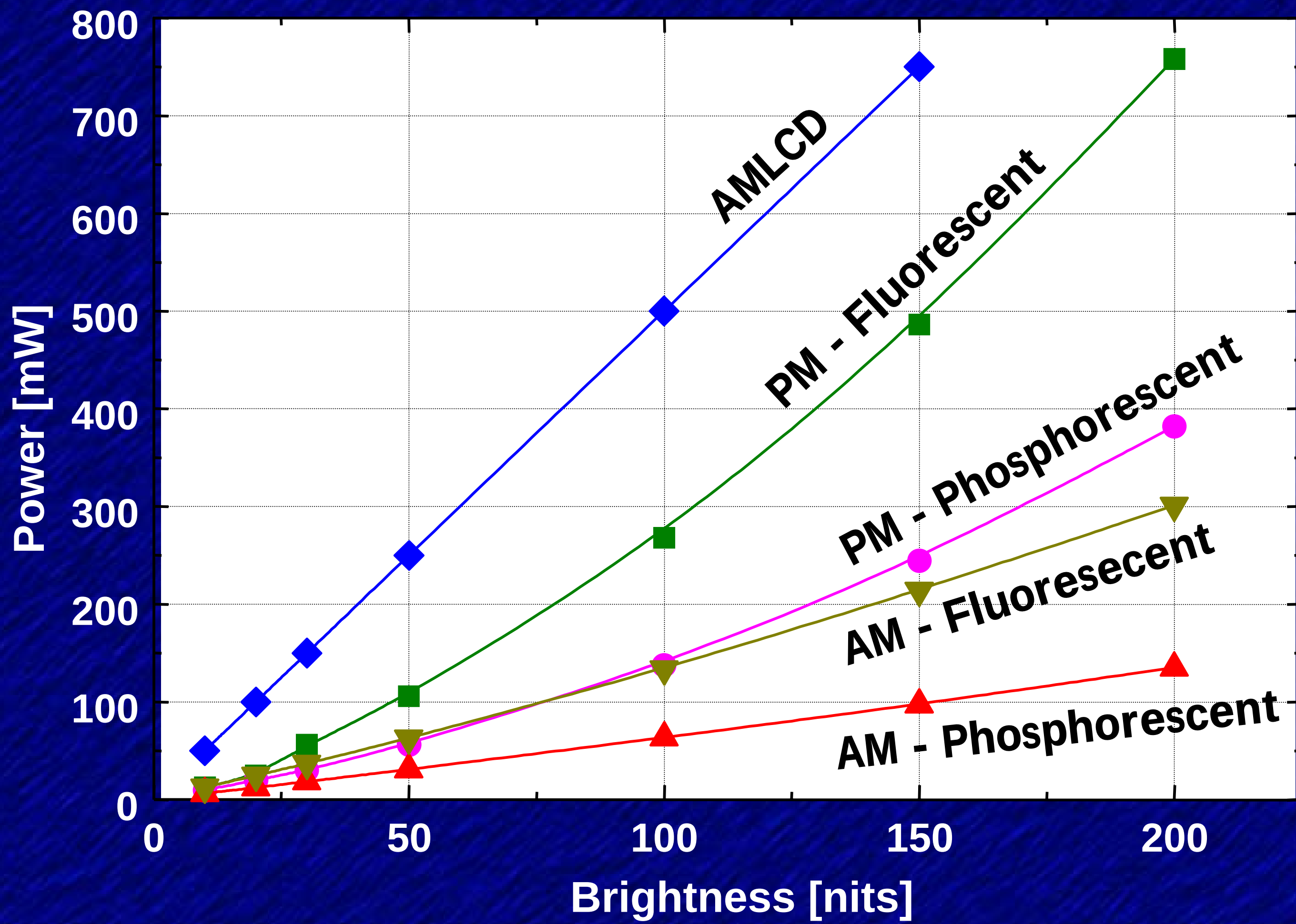
CBP



Simulated Power Consumption

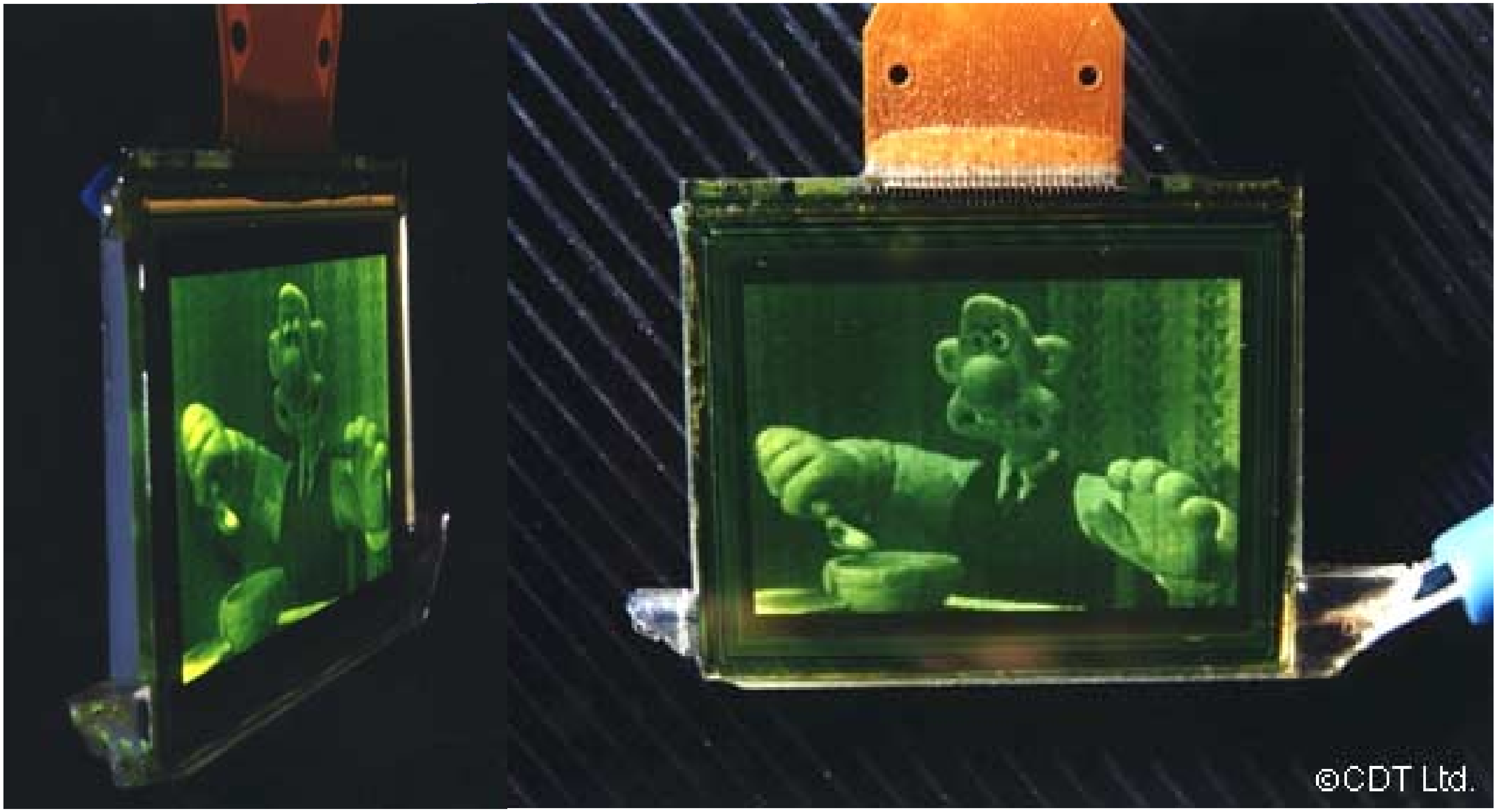
(5 inch/320x240 pixels monochrome display)

33% pixels "on"



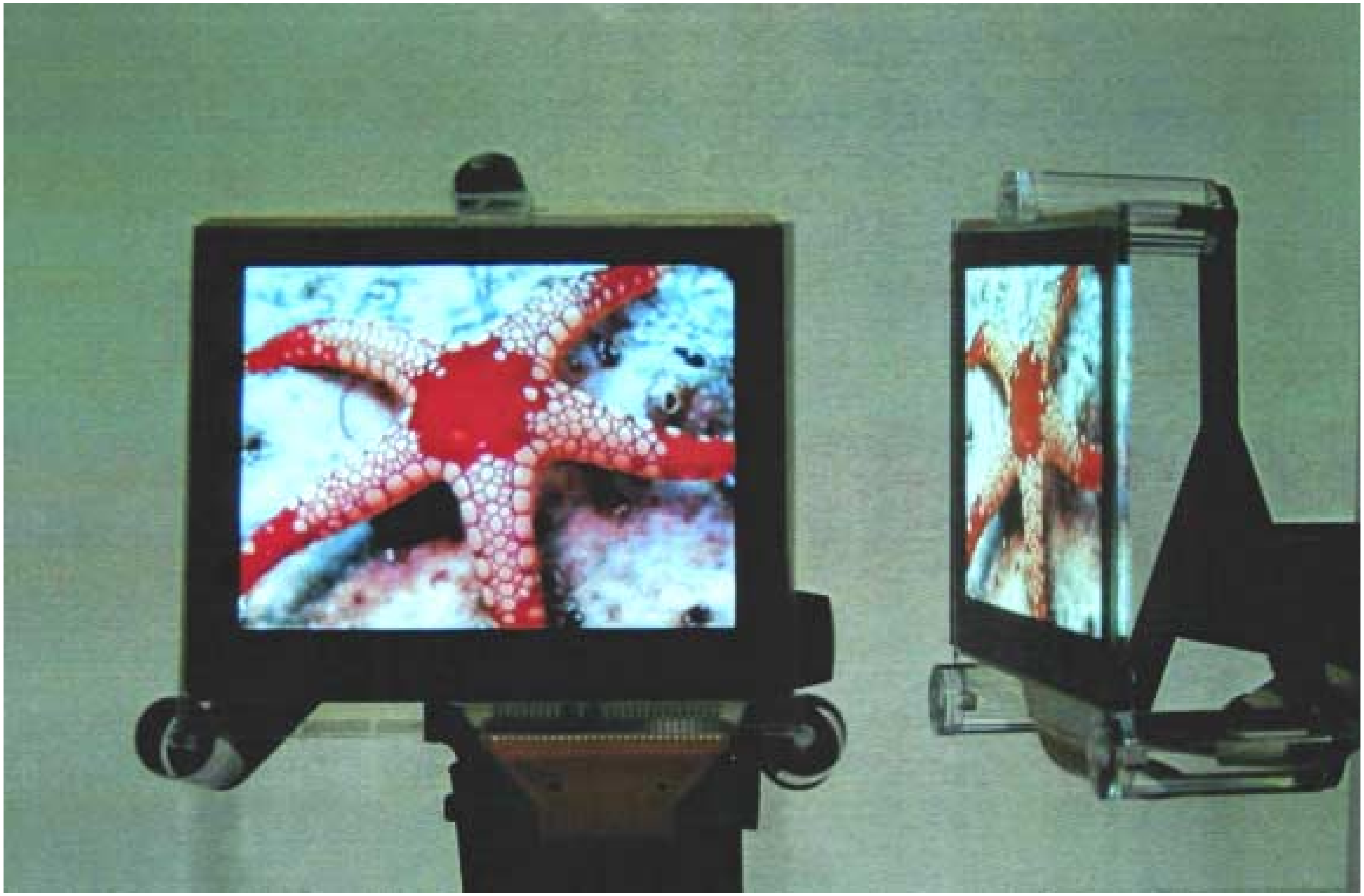
UDC, Inc.

Monochrome Passive-Matrix Polymer-LED Display



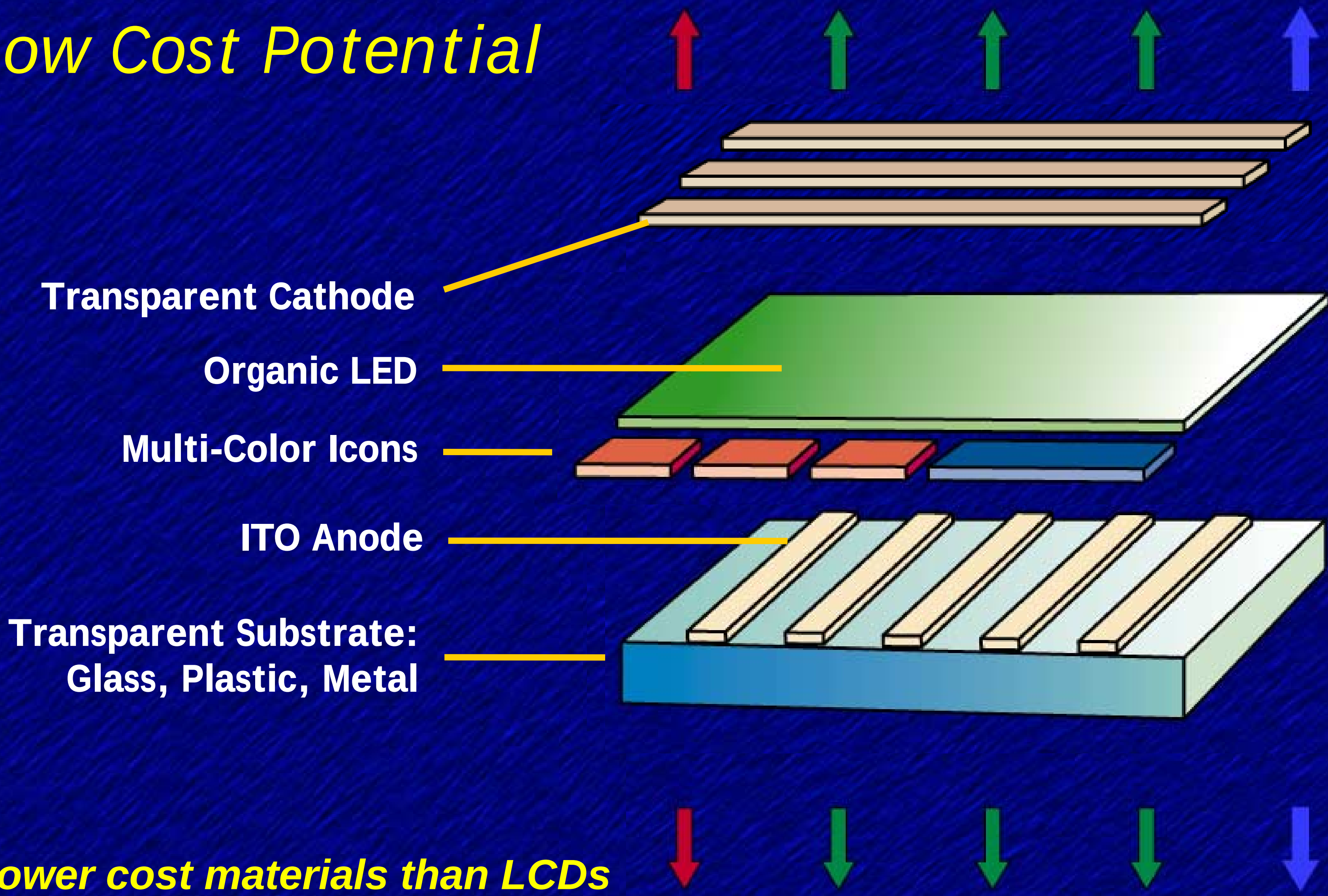
Cambridge Display Technologies, Ltd.

Full-Color OLED Display



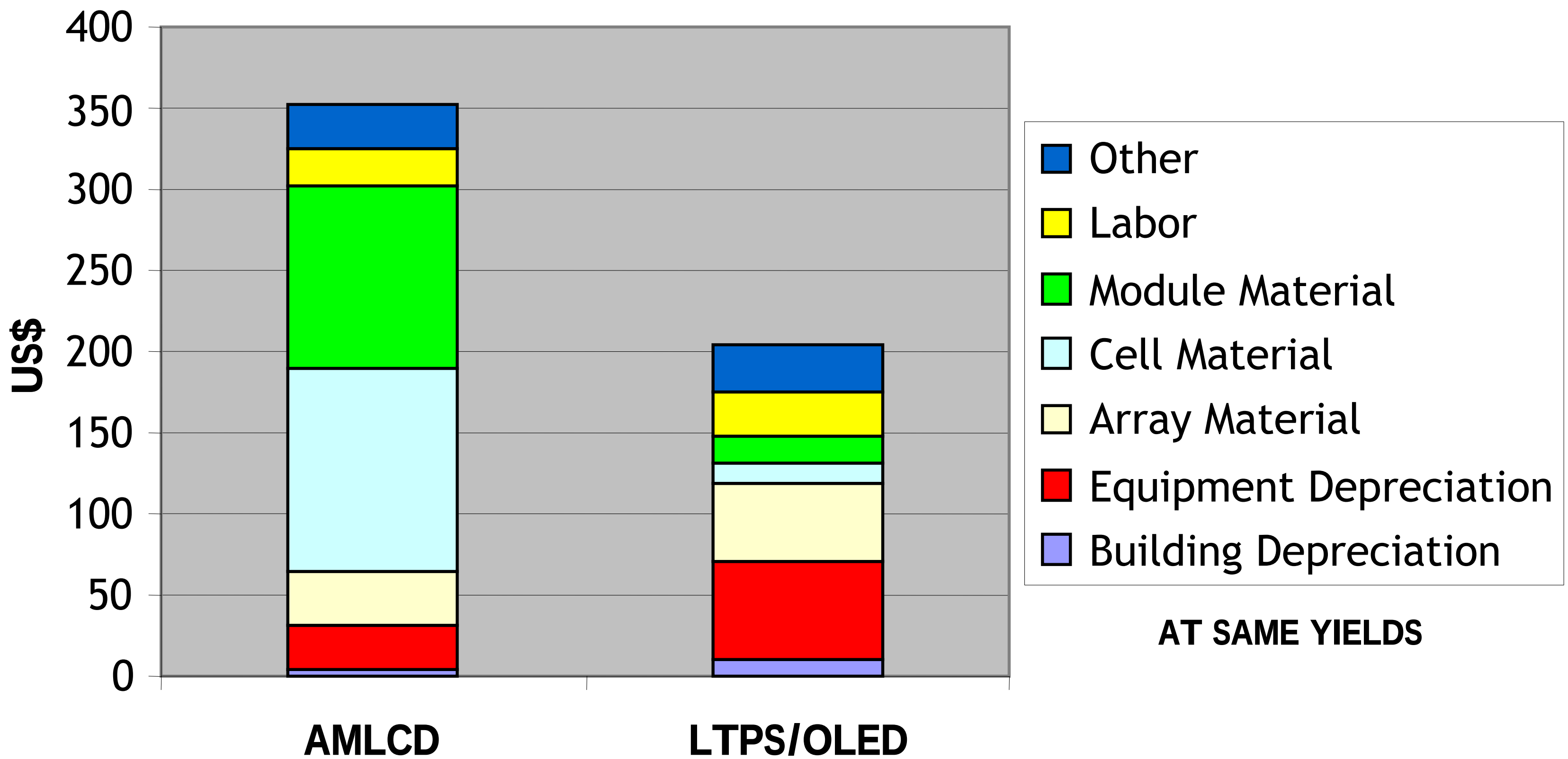
Kodak - Sanyo

Low Cost Potential



- *Lower cost materials than LCDs*
- *Fewer process steps than LCDs*
- *Less capital cost than LCDs*

15” XGA Cost Comparison

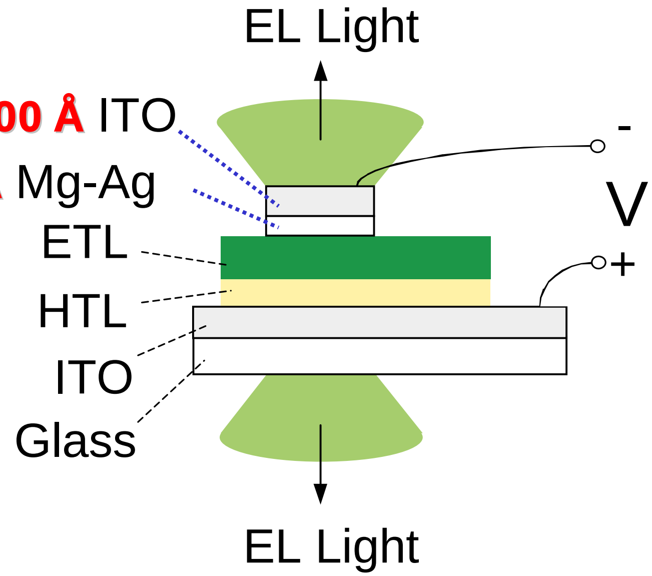


Source: DisplaySearch

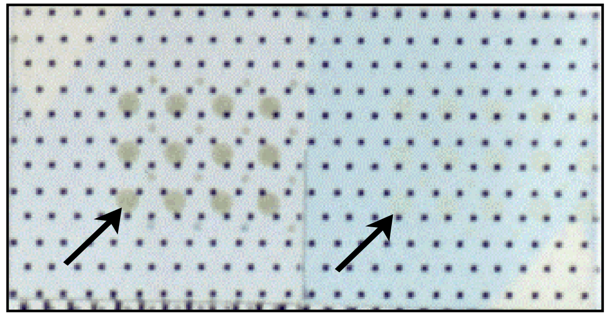
Technology Landscape

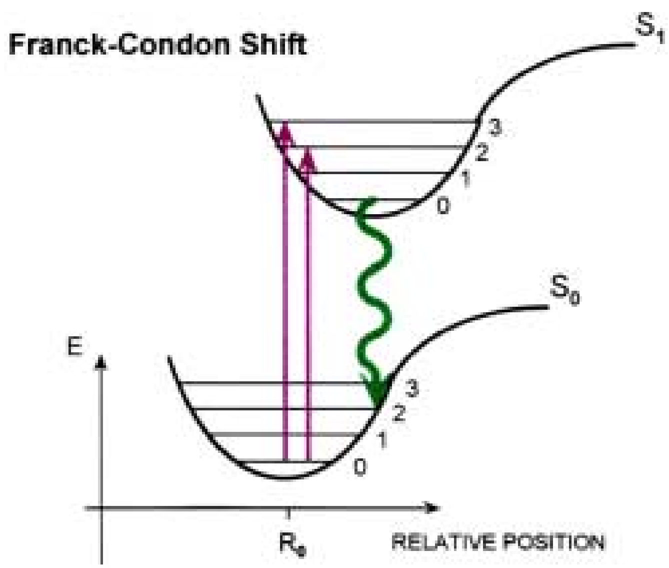
TECHNOLGY/ FEATURES	AMLCD	PMLCD	LED	PDP	FED	**OLED**
Brightness	Good	Good	Very Good	Good	Good	**Very Good**
Resolution	High	High	Low	Medium	High	**High**
Voltage	Low	Low	High	High	High	**Low**
Viewing Angle	Medium	Poor	Excellent	Excellent	Excellent	**Excellent**
Contrast Ratio	Good	Fair	Good	Poor-Good	Good	**Excellent**
Response Time	Good	Poor	Fast	Very Fast	Very Fast	**Very Fast**
Power Efficiency	Good	Good	Fair-Good	Medium	Very Good	**Very Good**
Temp Range	Poor	Poor	Very Good	Very Good	Very Good	**Very Good**
Form Factor	Thin	Thin	Wide	Wide	Thin	**Very Thin Conformable**
Weight	Light	Light	Above Avg.	Heavy	Light	**Light**
Screen Size	Small-Large	Small to Medium	Small to Large	Large	Medium	**Small to Large**
Primary Applications	Laptops, Desktop	Small Display	Signs, Indicators	Large Screen	Multiple	**Multiple New/Existing**
Cost	Average	Low	High	High	Average	**Below Average**

Transparent OLEDs



TOLEDs MF-TOLEDs





Alphanumeric TOLED Display

> 70% transparent

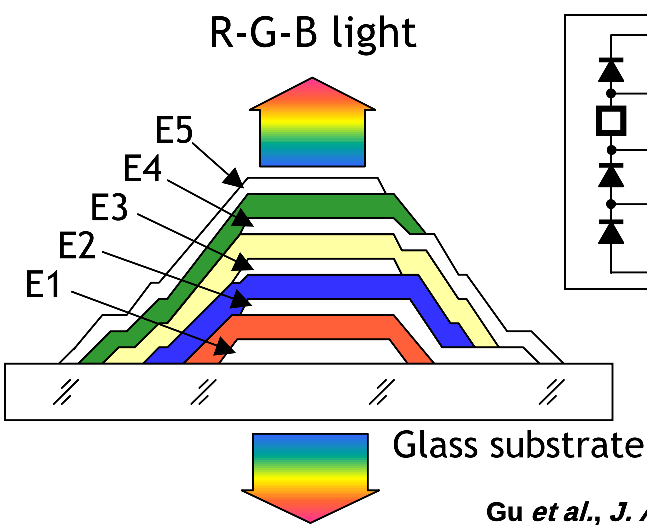
Bulović *et al.*, *Nature* 380, 29 (1996).
Parthasarathy *et al.*, *Appl. Phys. Lett.* 72, 2138 (1998).

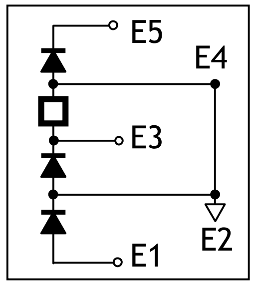
TOLED Applications

UDC, Inc.

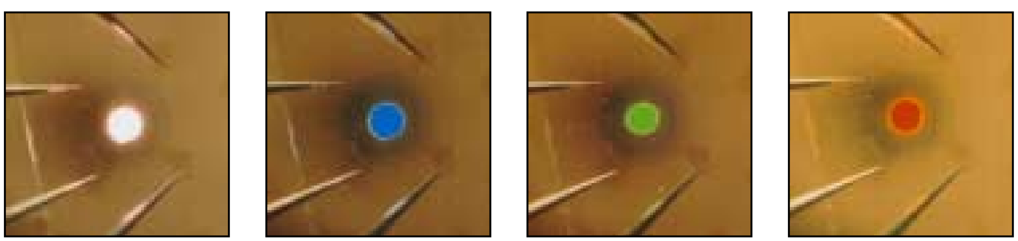
Stacked Organic LEDs (SOLEDs)

head-up, high resolution, true-color, high-contrast, brightly-emissive, flexible displays



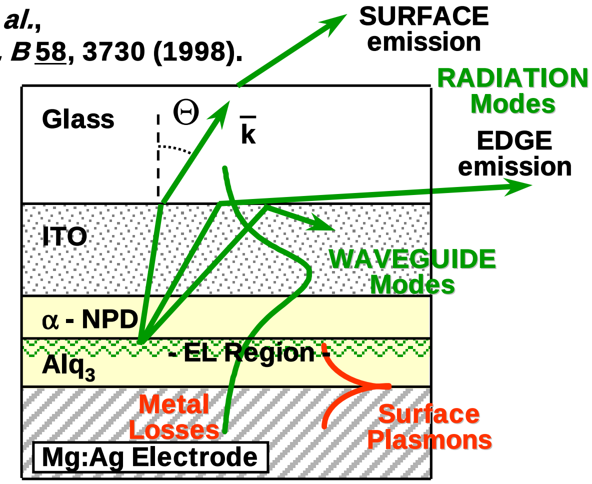


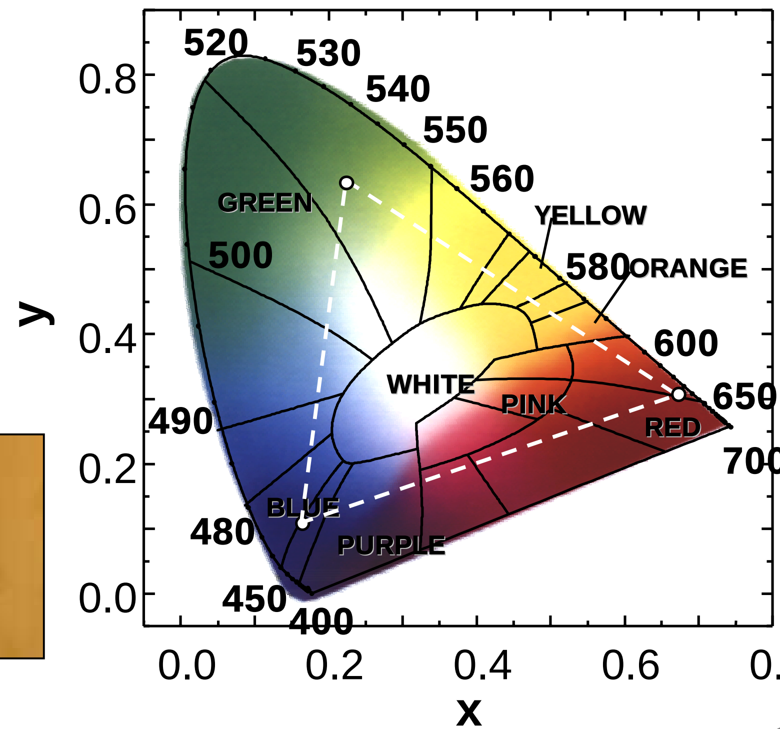
Gu *et al.*, *J. Appl. Phys.* (1999).
Shen *et al.*, *Science* 276, 2009 (1997).



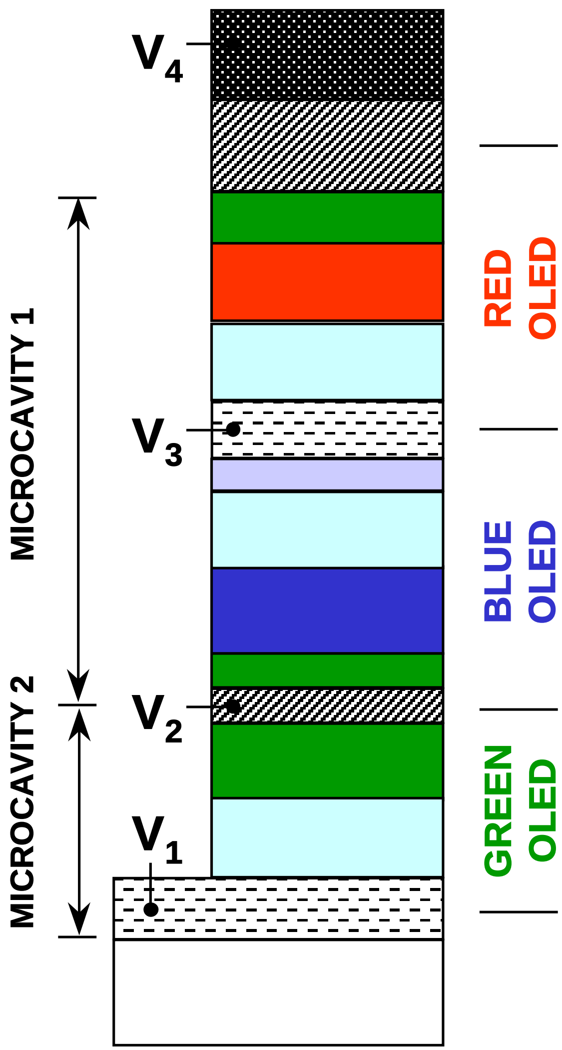
Microcavity Effects

Bulović *et al.*, *Phys. Rev. B* 58, 3730 (1998).





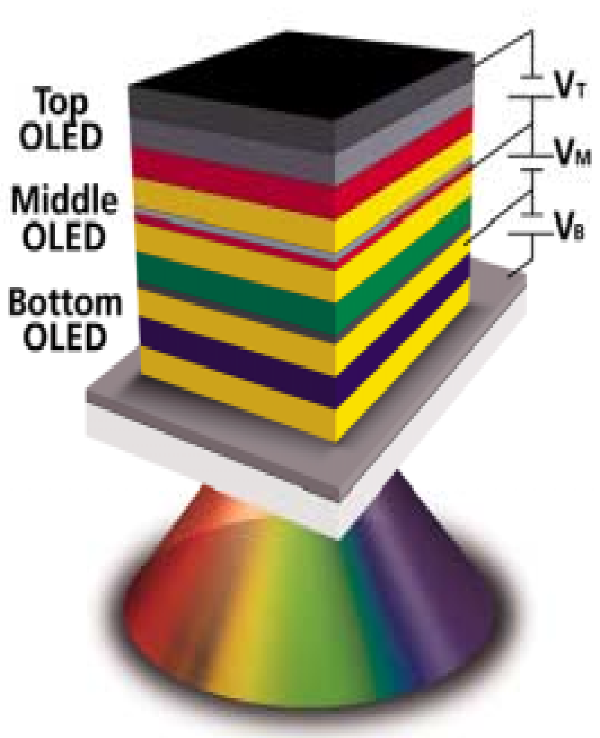
Example of a Stacked OLED Structure

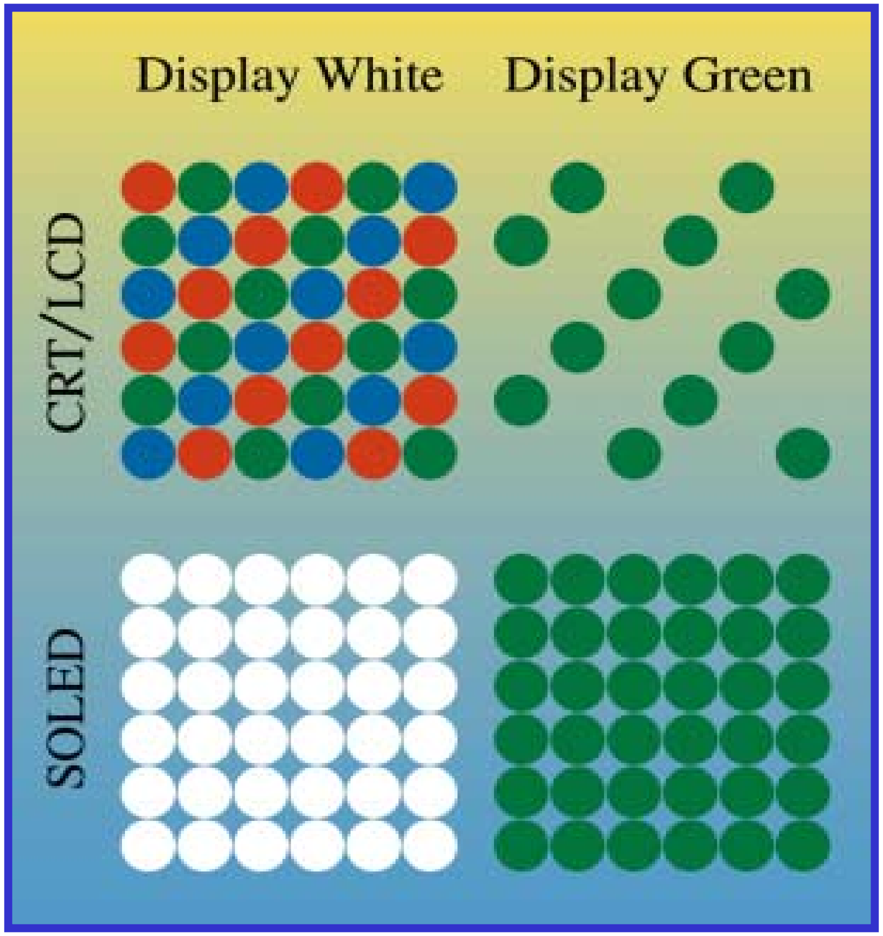


MATERIAL	THICKNESS [Å]	n
Ag	1000	----
Mg:Ag	1000	----
Alq_3	170	1.72
3% DCM2 in Alq_3	330	1.72
α-NPD	540	1.78
ITO	490	2.02
CuPc	80	1.5+0.8i
α-NPD	250	1.77
Alq'_2OPh	390	1.66
Alq_3	50	1.72
Mg:Ag	80	----
Alq_3	540	1.72
α-NPD	445	1.77
ITO	1600	1.8
Glass	~1 mm	1.45

Advantages of Stacked OLEDs

True-Color Pixels

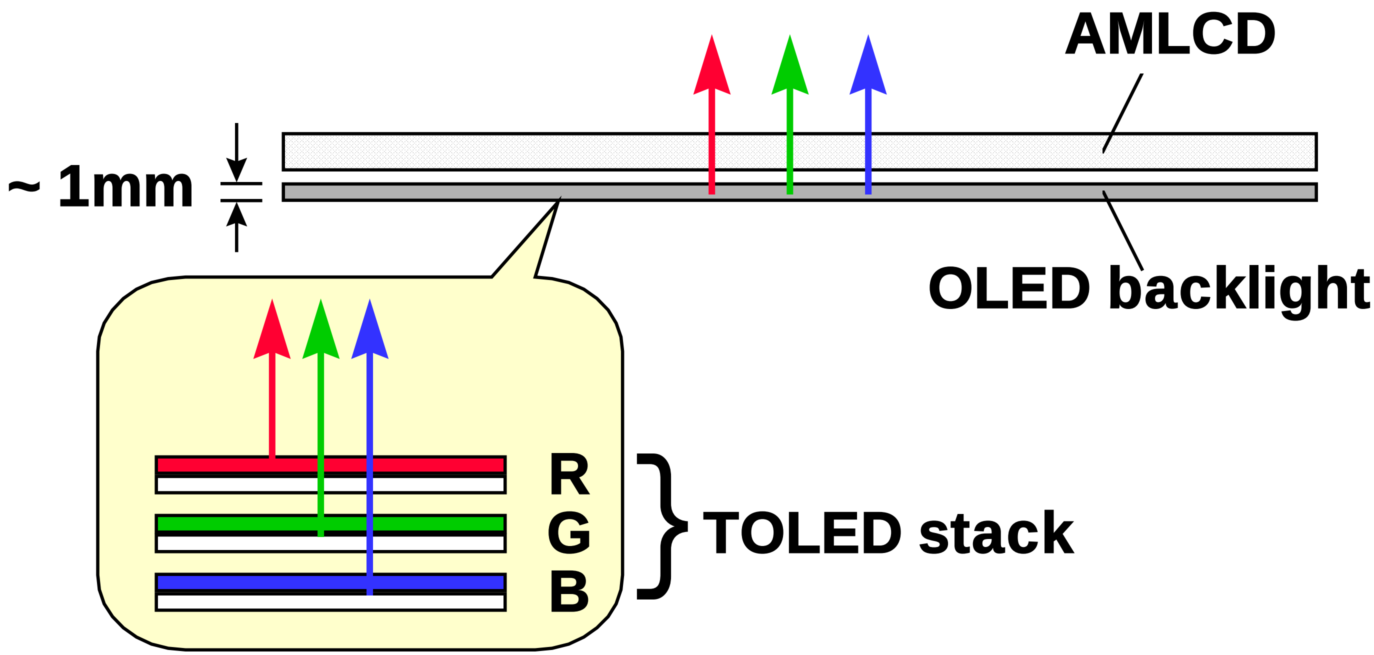




Up to 3 times the resolution of conventional displays

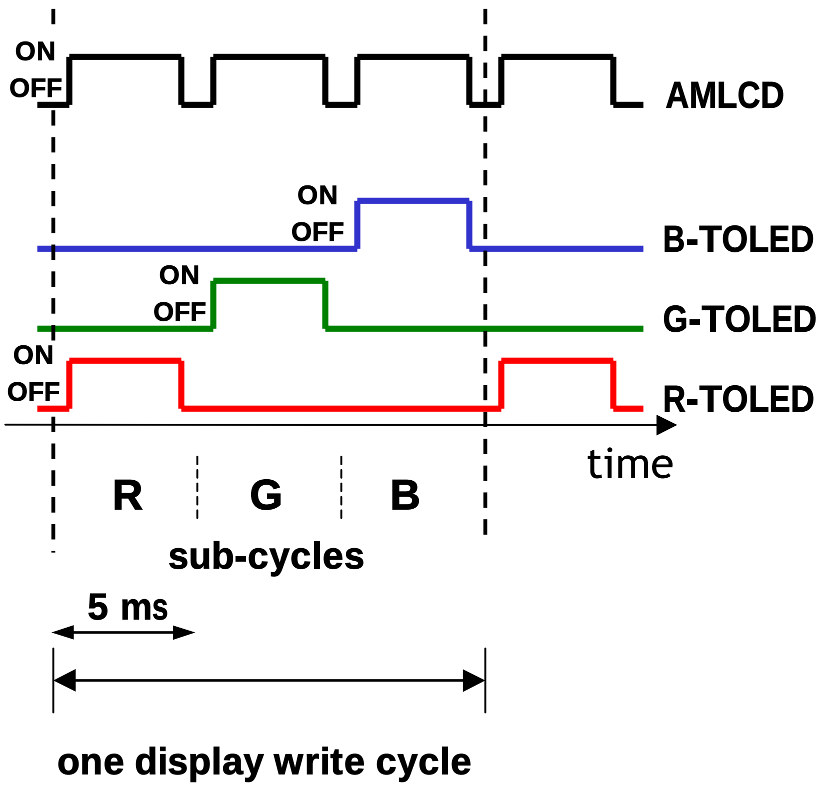
Organic LED Backlight Integrated with an AMLCD

for full-color displays the backlight can consist of a stack of R,G, and B TOLED backlights

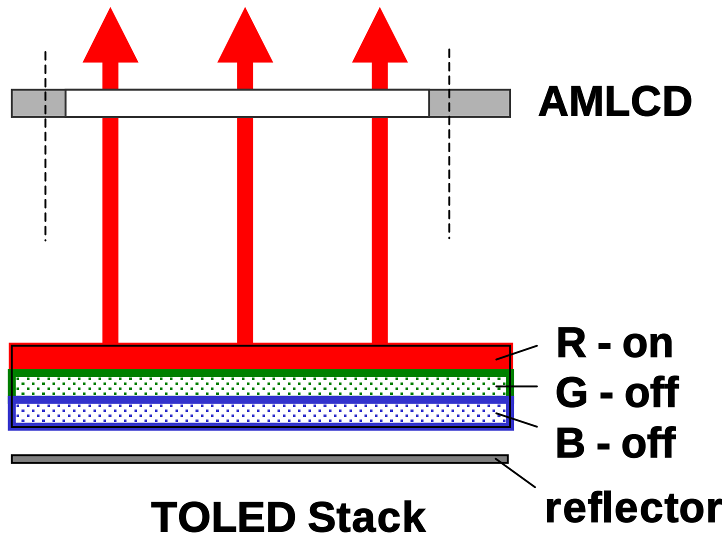


Principle of OLED Backlight Operation

Timing Diagram



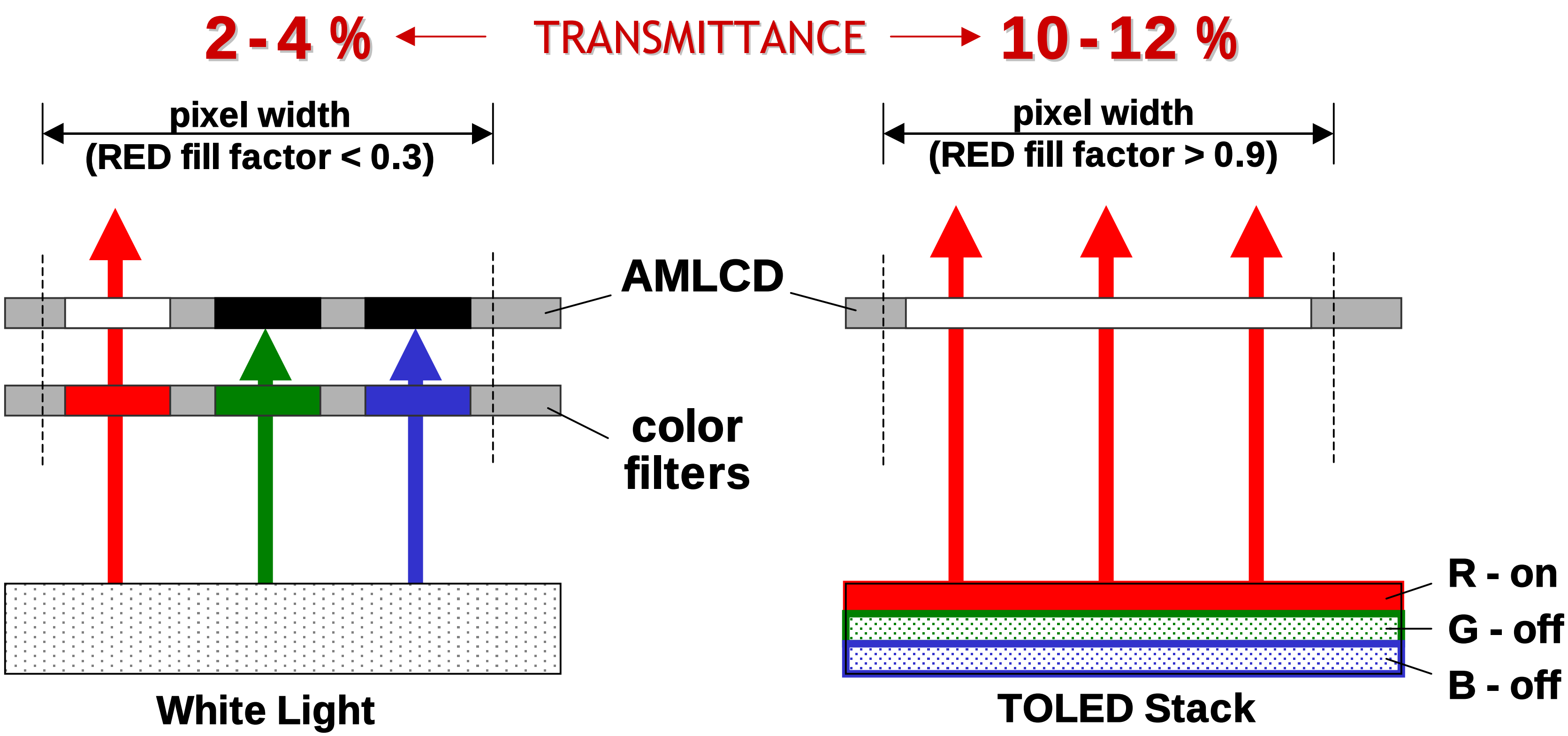
R sub-cycle



Response Times

OLED rise time ~ 1μs
LCD response time ~ 5 ms

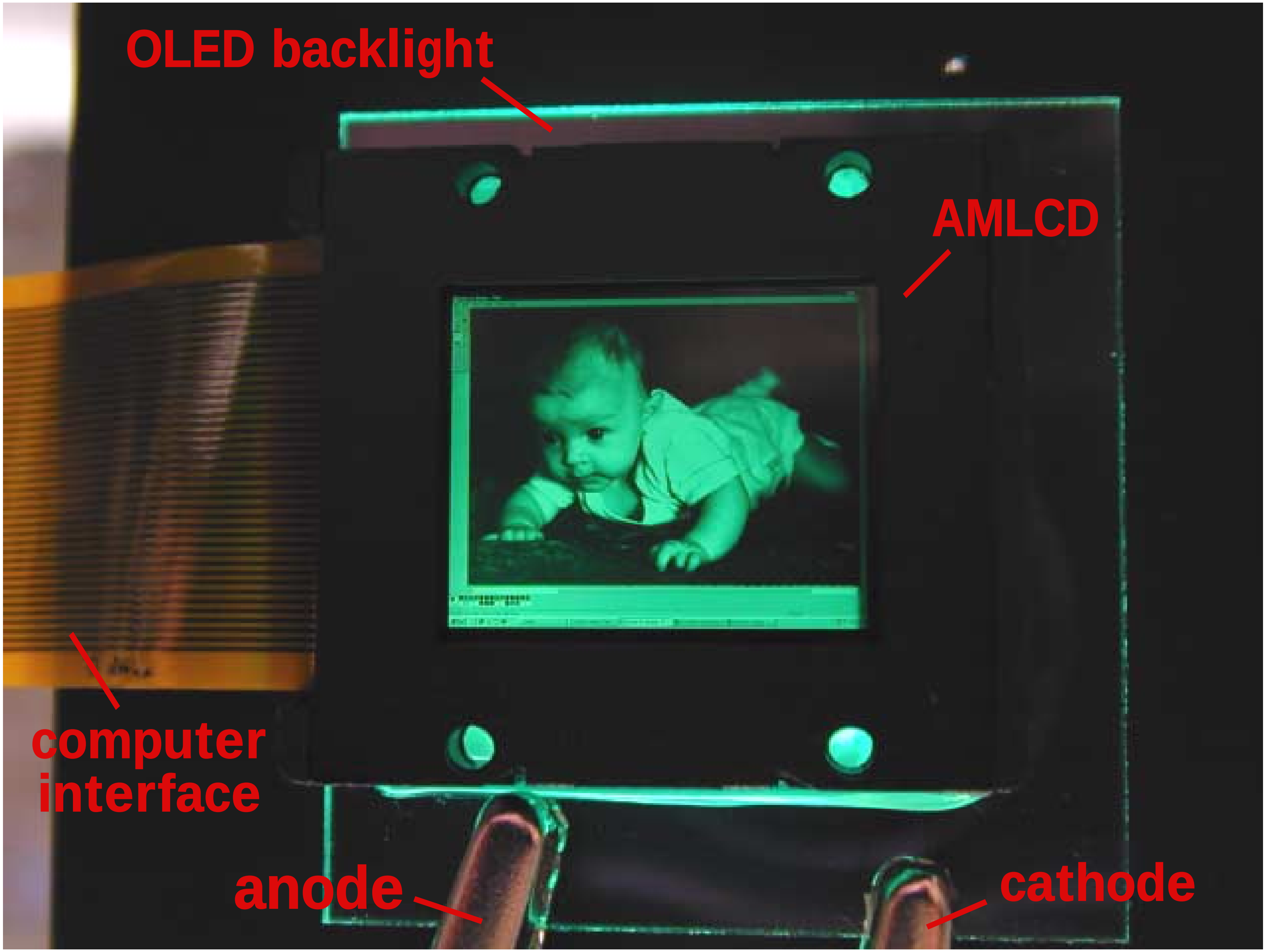
White Backlight vs. TOLED R,G,B Stack



ADVANTAGES OF TOLED STACK BACKLIGHTS

- AMLCD with no sub pixels ⇒ larger fill factor
- no color filters ⇒ more efficient use of backlight emitted light

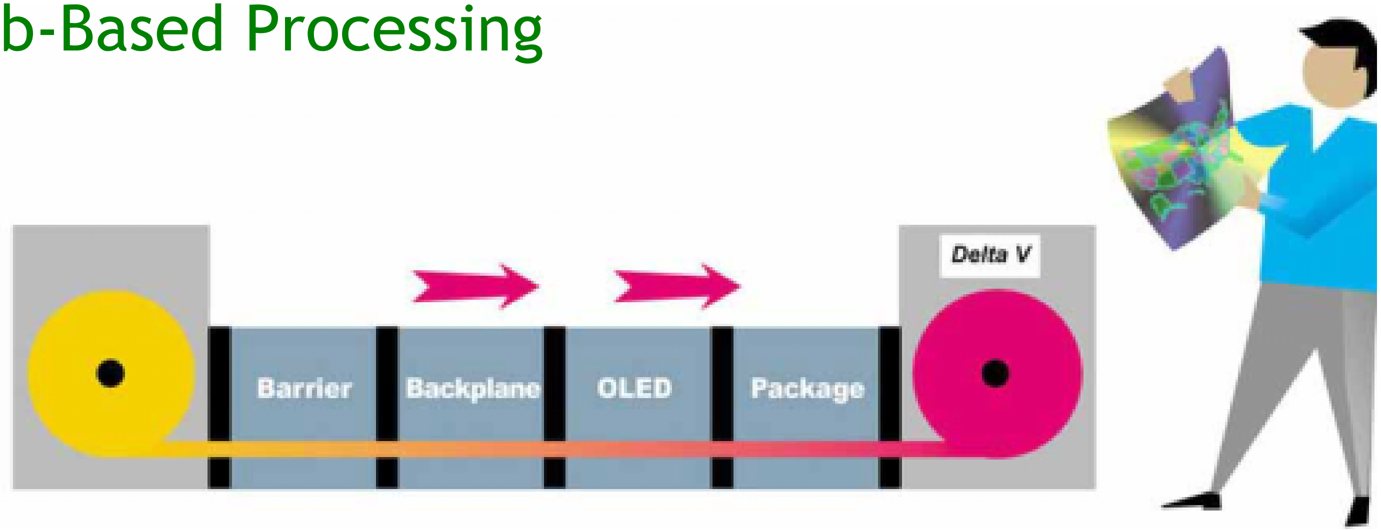
3 to 6 fold improvement in efficiency


OLED backlight
AMLCD
computer
interface
anode
cathode

Flexible OLED (FOLED)

- Ultra lightweight
- Thin form factor
- Rugged
- Impact resistant
- Conformable

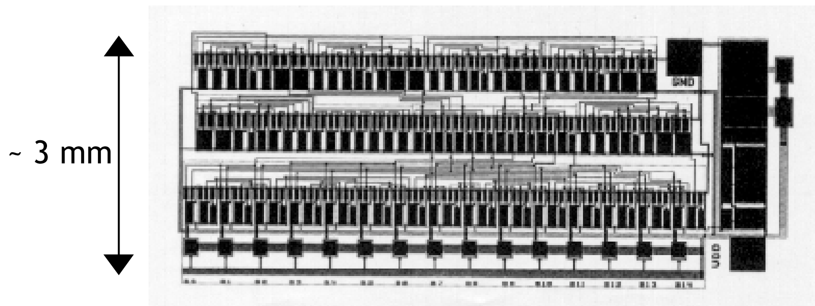
Manufacturing Paradigm Shift
Web-Based Processing



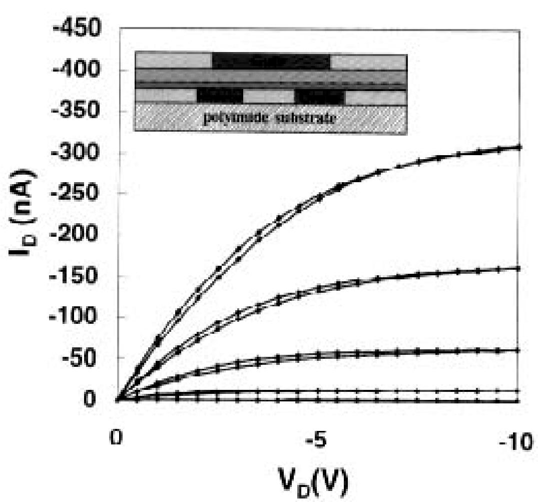
Low-Cost All-Polymer Integrated Circuits

Drury *et al.*, *Appl. Phys. Lett.* **73**, 108 (1998).

LAYOUT

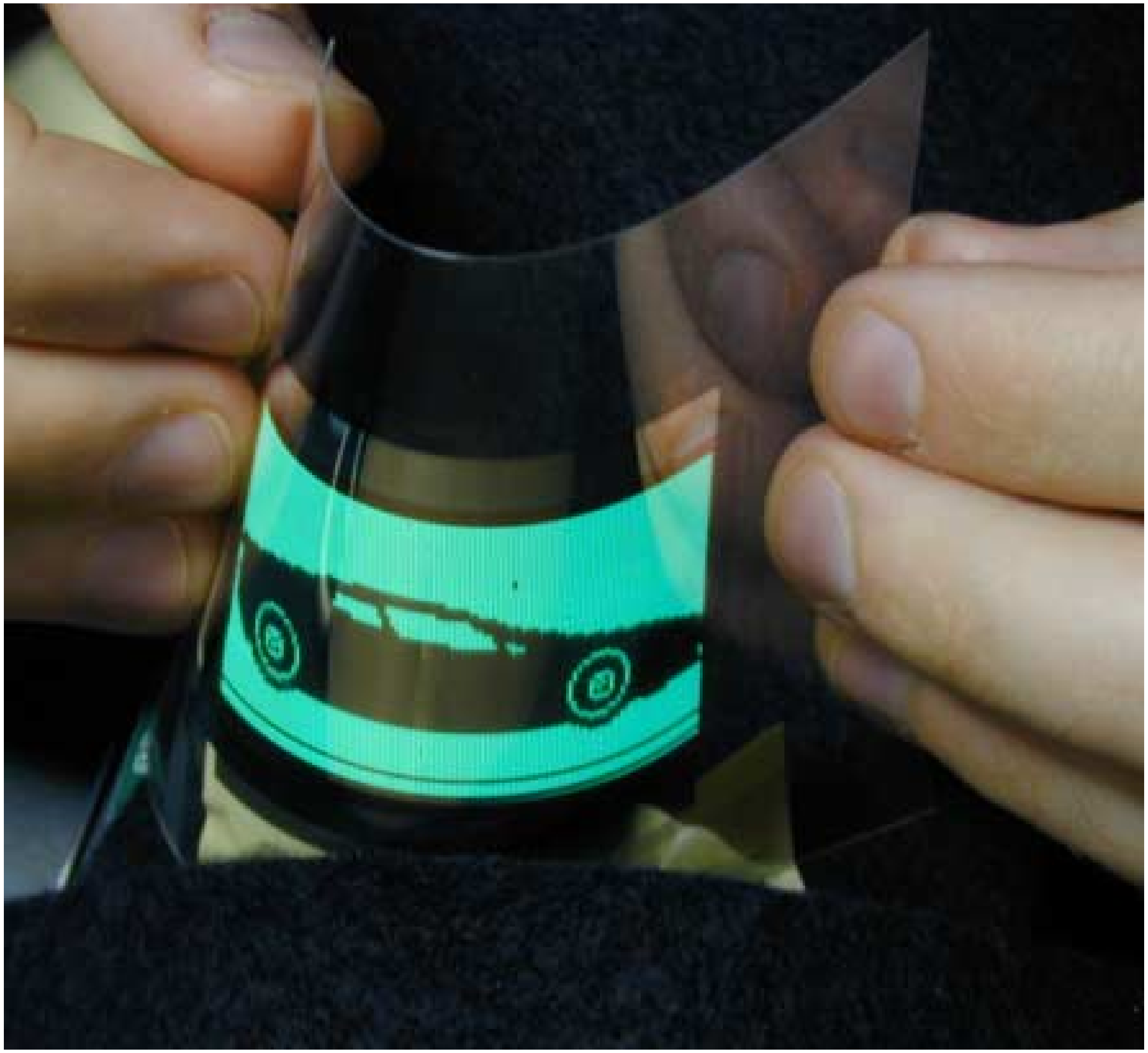


I_D - V_D RESPONSE



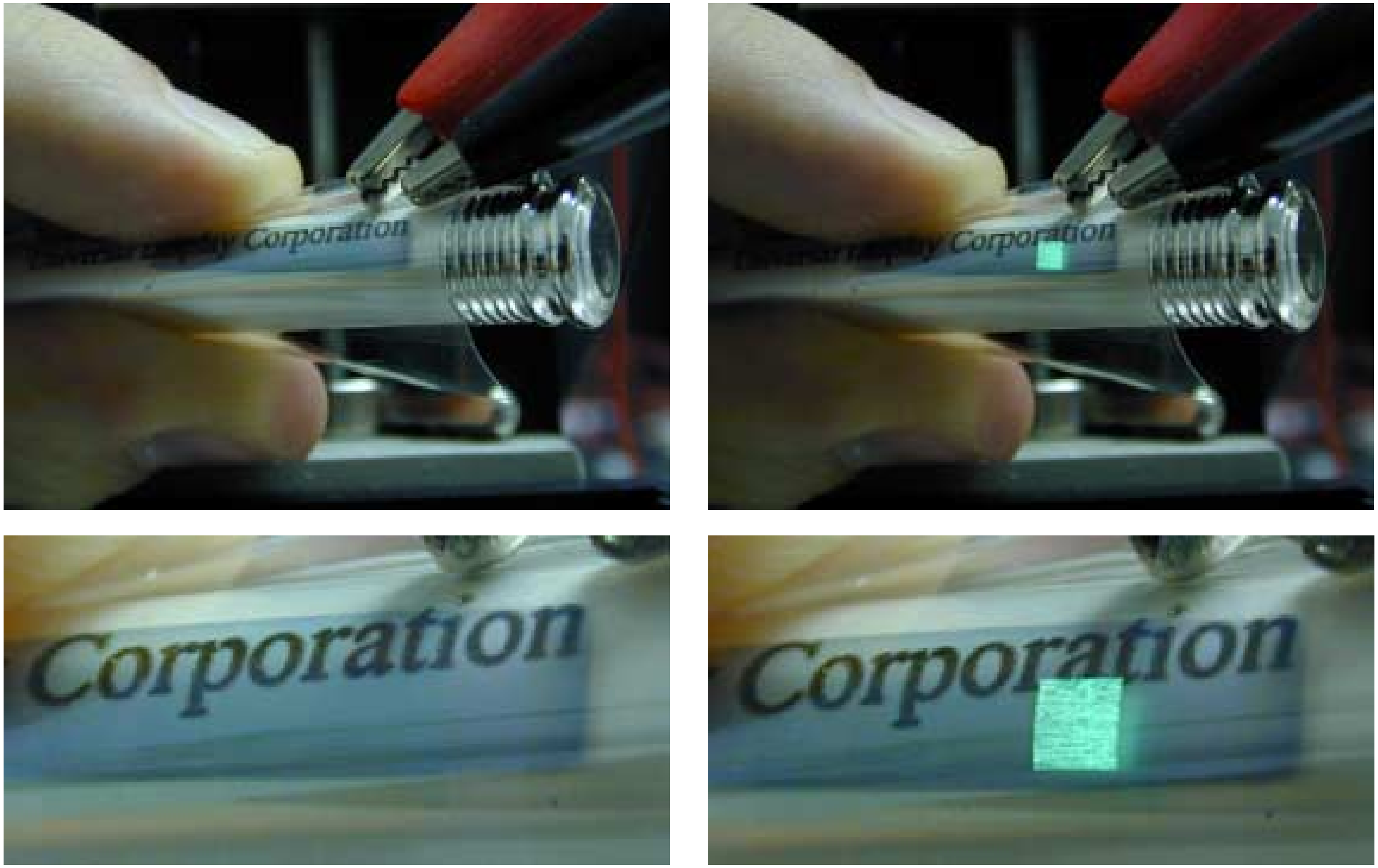
- 15 bit programmable code generator
- 326 all-polymer transistors (2μm x 1mm gates) with vertical interconnections
- $\mu_{channel}$ = 3 x 10^{-4} cm^2/Vs, 40-200 Hz bandwidth
- 3” diameter polyimide substrate

FOLED-based Pixelated, Monochrome Display



Source: UDC, Inc.

Transparent FOLED-based Pixel



Source: UDC, Inc.

The PRESENT ...

... and the nearby FUTURE ...

... of ORGANIC DISPLAY TECHNOLOGY