Emissive Displays - Organic Electroluminescence

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

MOLECULAR MATERIALS

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
  - $5 \times 10^{-7}$ Torr
  - Room T
  - 20 to 2000 Å layer thickness
Materials Growth Laboratory

Base Pressure $10^{-9} \sim 10^{-11}$ torr

OMBD II
Sputtering
OMBD I
Metal e-Beam
III-V MBE

Analysis Chamber
Load Lock
Transfer Chamber
Load Lock

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

©CDT Ltd.
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

©CDT Ltd.
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

Diagram showing the layers of the OLED: Glass, ITO, TPD, Alq3, Mg:Ag, Ag, and the light emission regions labeled HOMO and LUMO.
Electroluminescence

Single Layer Device

Heterostructure Device
Exciton Recombination Zone

C. Adachi, et al.
Trap Limited Conduction in Organic Materials

charge trapping can dominate conduction

\[ \Rightarrow \Delta E \]

free molecule

molecule distorts

\[ E \]

\[ \Delta E \]

\[ \text{LUMO} \]

\[ \text{HOMO} \]

\[ J \propto N_{\text{LUMO}} \mu_n N_t^{m \frac{\Delta E}{k_B T}} \Delta E^{m+1} \]

\[ m = \frac{T_t}{T} \]

\[ N_t = 3.1 \times 10^{18} \text{cm}^{-3} \]

\[ \mu_n N_{\text{LUMO}} = 4.8 \times 10^{14} / \text{cm-V-s} \]

Progress in LED Efficiency

**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)
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)

OLED Stability
1. Excitons formed from combination of electrons and holes

2. Excitons transfer to luminescent dye
Effect of Dopants on the OLED EL Spectrum

![Graph showing the normalized EL intensity as a function of wavelength for different dopants.]

- Alq3
- PtOEP:Alq3
- DCM2:Alq3
- α-NPD

Wavelength [nm]
Solid State Solvation Effect


EL Spectrum Tuning

[Graph showing EL intensity vs. wavelength for DCM2 in Alq3 with different concentrations (10%, 5%, 2%, 1%, 0%) of DCM2 in Alq3, indicating wavelength shifts and intensity changes.]

Temporal Response

[Graph showing temporal response with wavelength shifts from 600 to 750 nm, including 1.00 ns, 0.75 ns, 0.50 ns, and 0.25 ns temporal shifts, and intensity changes up to 16 a.u.]
Influence of $\mu_0$ and $\mu_1$ on Chromatic Shift Direction

\[ \mu_0 < \mu_1 \]

\[ \mu_0 > \mu_1 \]
Solid State Solvation Effect (SSSE)

"self polarization" for strongly dipolar lumophores

\[ \langle \mu \rangle > 0 \]
\[ \langle \mu \rangle \to 0 \quad \text{as } R \to \text{ large} \]
Thin Film Photoluminescence

DCM2 in $\text{Alq}_3$
- polar host
- $\mu \sim 5.5$ D

DCM2 in $\text{Zrq}_4$
- non-polar host
Tuning Emission of White OLEDs

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

changing BCP layer thickness (with 0.6% DCM2)

- Alq$_3$
- BCP
- NPD:DCM2
- TPD
- ITO
- glass

Ag
Mg:Ag

Intensity [a.u.]

Wavelength [nm]
**Fluorescence**

- Singlet excited state $S_1$
- Triplet excited state $T_1$
- Ground state (singlet) $S_0$

- Symmetry conserved
- Fast process $\sim 10^{-9}$s

**Phosphorescence**

- Singlet excited state $S_1$
- Triplet excited state $T_1$
- Ground state (singlet) $S_0$

- Triplet to ground state transition is not permitted
- Slow process $\sim 1s$
**Phosphorescent OLED Performance**

6% \( \text{Ir}(ppy)_3 \) 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
Simulated Power Consumption
(5 inch/320x240 pixels monochrome display)
33% pixels “on”

Power [mW] vs Brightness [nits]

- AMLCD
- PM - Fluorescent
- PM - Phosphorescent
- AM - Fluorescent
- AM - Phosphorescent

UDC, Inc.
Monochrome Passive-Matrix Polymer-LED Display

Cambridge Display Technologies, Ltd.
Full-Color OLED Display

Kodak - Sanyo
Transparent Substrate:
Glass, Plastic, Metal

Low Cost Potential

Transparent Cathode
Organic LED
Multi-Color Icons
ITO Anode
Transparent Substrate: Glass, Plastic, Metal

• Lower cost materials than LCDs
• Fewer process steps than LCDs
• Less capital cost than LCDs
15” XGA Cost Comparison

Source: DisplaySearch
<table>
<thead>
<tr>
<th>TECHNOLOGY/FEATURES</th>
<th>AMLCD</th>
<th>PMLCD</th>
<th>LED</th>
<th>PDP</th>
<th>FED</th>
<th>OLED</th>
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<tbody>
<tr>
<td>Brightness</td>
<td>Good</td>
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<td>Very</td>
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<td>Poor-Good</td>
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<td>Fair-Good</td>
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<td>Form Factor</td>
<td>Thin</td>
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<td>Wide</td>
<td>Wide</td>
<td>Thin</td>
<td>Very Thin Conformable</td>
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<td>Weight</td>
<td>Light</td>
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<td>Heavy</td>
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<td>Screen Size</td>
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<td>Small to Medium</td>
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<td>Primary Applications</td>
<td>Laptops, Desktop</td>
<td>Small Display</td>
<td>Signs, Indicators</td>
<td>Large Screen</td>
<td>Multiple</td>
<td>Multiple New/Existing</td>
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<td>Cost</td>
<td>Average</td>
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<td>High</td>
<td>Average</td>
<td>Below Average</td>
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</table>
**Transparent OLEDs**

ITO

Mg-Ag

ETL

HTL

ITO

Glass

EL Light

$500 \text{ Å}$

$50-100 \text{ Å}$

Alphanumeric TOLED Display

> 70% transparent

I - V Characteristics of a Metal Free-TOLED

\[ I \propto V^9 \]

\[ I \propto V^2 \]

- MF-TOLED
- TOLED

**Diagram:**
- ITO
- CuPc
- Alq\(_3\)
- \(\alpha\)-NPD
- CuPc
- ITO
- Glass
- EL
Transparency/Reflection of a Metal Free-TOLED

![Graph showing CuPc Absorption, Transmission, and Reflection over a range of wavelengths from 500 to 800 nm. The y-axis represents intensity in arbitrary units (a.u.).]
Schematic Cross-Sections of Monochrome OLEDs

**NON-TRANSPARENT DEVICES**

- **Conventional OLED**
  - Anode: ITO
  - Cathode: Mg:Ag, Alq₃, TPD, ITO, Glass
  - Voltage: V⁺, V⁻

**TRANSPARENT DEVICES**

- **TOLED**
  - Anode: ITO
  - Cathode: Mg:Ag, Alq₃, TPD, ITO, Glass
  - Voltage: V⁺, V⁻

- **OLED**
  - Anode: ITO, PTCDMA
  - Cathode: Mg:Ag, Alq₃, TPD, ITO, Glass
  - Voltage: V⁺, V⁻

- **TOI-LED**
  - Anode: ITO, PTCDMA
  - Cathode: Mg:Ag, Alq₃, TPD, ITO, Glass
  - Voltage: V⁺, V⁻
TOLED Applications
Stacked Organic LEDs (SOLEDs)

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

R-G-B light

Glass substrate


Microcavity Effects


Glass substrate

### Example of a Stacked OLED Structure

<table>
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<tr>
<th>MATERIAL</th>
<th>THICKNESS [Å]</th>
<th>n</th>
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<tbody>
<tr>
<td>Ag</td>
<td>1000</td>
<td>---</td>
</tr>
<tr>
<td>Mg:Ag</td>
<td>1000</td>
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<tr>
<td>Alq₃</td>
<td>170</td>
<td>1.72</td>
</tr>
<tr>
<td>3% DCM2 in Alq₃</td>
<td>330</td>
<td>1.72</td>
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<tr>
<td>α-NPD</td>
<td>540</td>
<td>1.78</td>
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<tr>
<td>ITO</td>
<td>490</td>
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<tr>
<td>CuPc</td>
<td>80</td>
<td>1.5+0.8i</td>
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<tr>
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<td>Alq’₂OPh</td>
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<tr>
<td>Alq₃</td>
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<td>1.72</td>
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<tr>
<td>Mg:Ag</td>
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<td>Alq₃</td>
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<td>1.72</td>
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<tr>
<td>α-NPD</td>
<td>445</td>
<td>1.77</td>
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<tr>
<td>ITO</td>
<td>1600</td>
<td>1.8</td>
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<tr>
<td>Glass</td>
<td>~1 mm</td>
<td>1.45</td>
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</tbody>
</table>
Advantages of Stacked OLEDs

True-Color Pixels

Up to 3 times the resolution of conventional displays
A Method for Depositing a Multilayer SOLED Structure with Fanned Electrodes

(a) ANGLE DEPOSITION WITH A STATIONARY SUBSTRATE

(b) ANGLE DEPOSITION WITH A ROTATING SUBSTRATE

(c) TWO-COLOR STACKED OLED
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**
  - OLED Stack:
    - R - on
    - G - off
    - B - off
  - Reflector
  - 5 ms
- **R TOLED**
  - ON
  - OFF
- **G TOLED**
  - ON
  - OFF
- **B TOLED**
  - ON
  - OFF

**Response Times**
- OLED rise time ~ 1 μs
- LCD response time ~ 5 ms
**White Backlight vs. TOLED R,G,B Stack**

![Diagram showing comparison between White Light and TOLED Stack](image)

**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
Other Approaches for Full-Color Displays

### Patterning of RGB Emitters
- **Advantage**
  - Without CF
  - Efficient light usage
- **Disadvantage**
  - Patterning?
  - → Insoluble polymer

### Microcavity
- **Advantage**
  - Color Purity
  - Without CF
  - Unpatterned LED
- **Disadvantage**
  - Viewing angle
  - Cost of mirror (SiO$_2$/TiO$_2$ 6 layers)

### White Emission with CF
- **Advantage**
  - Contrast
  - Color Purity
  - Unpatterned LED
- **Disadvantage**
  - With CF
  - Absorption Loss

### Blue Emission w/ Color Conversion
- **Advantage**
  - Efficient light usage
  - Color purity
  - Unpatterned LED
- **Disadvantage**
  - Need stable and efficient blue dyes
Flexible OLED (FOLED)

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

Manufacturing Paradigm Shift
Web-Based Processing
Low-Cost All-Polymer Integrated Circuits


LAYOUT

- 3 mm

I_D - V_D RESPONSE

- 15 bit programmable code generator
- 326 all-polymer transistors (2μm x 1mm gates) with vertical interconnections
- μ_{channel} = 3 \times 10^{-4} \text{ cm}^2/\text{Vs}, 40-200 \text{ 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**