OLEDs for General Illumination ?

Research & Development Issues

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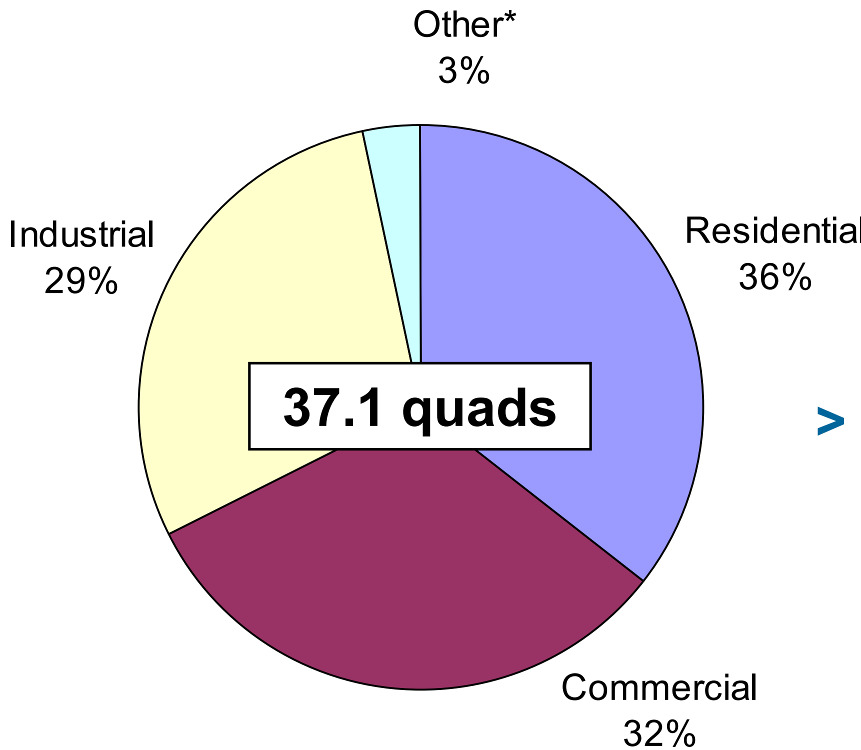
Milan Stolka

Total US Consumption of Energy for Electricity, 2001



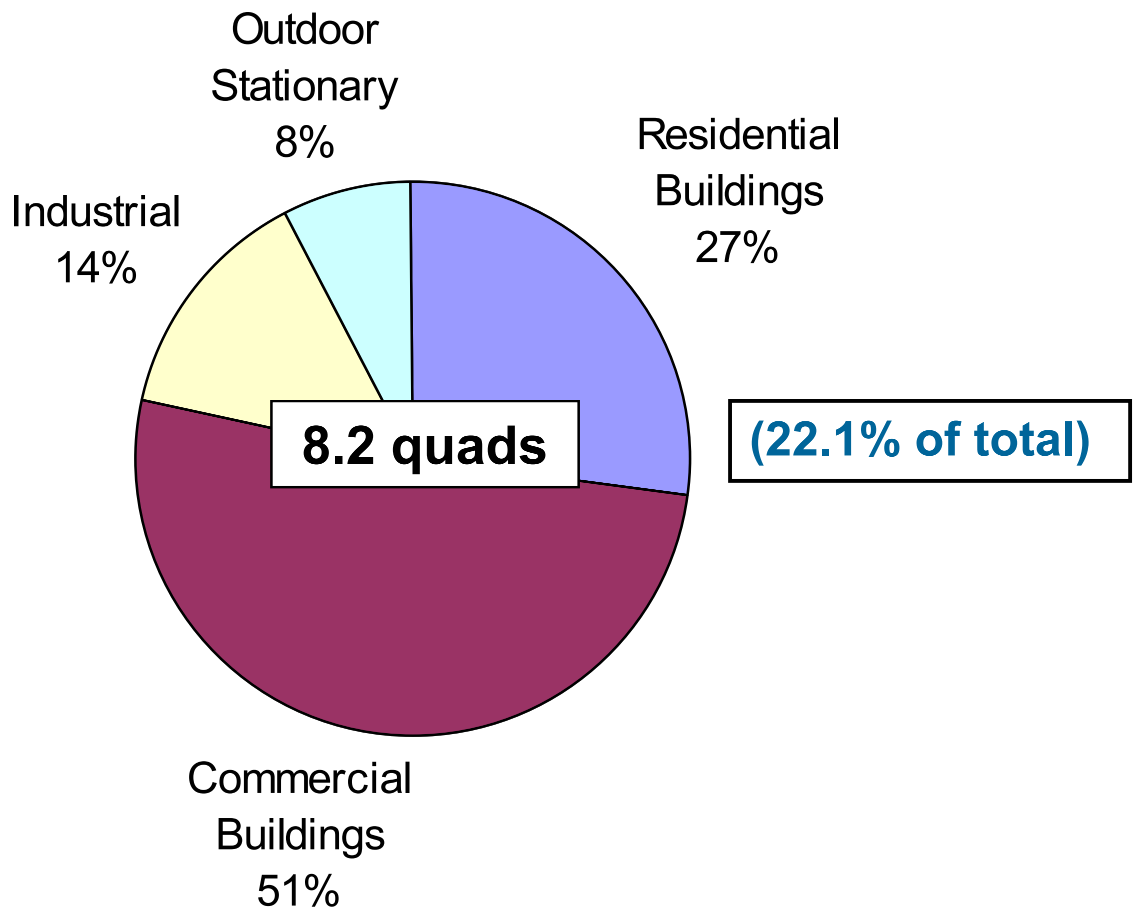
> $ 60 B / y

**** Other includes electricity for street lighting, public authorities, railways, irrigation, and interdepartmental sales.***

J. Brodrick, DOE

Source: Preliminary estimate, Table 44; Energy Information Administration, Form EIA-826, "Monthly Electric Utility Sales and Revenue Report with State Distributions."

Energy Consumption for Lighting by Building Sector, 2001

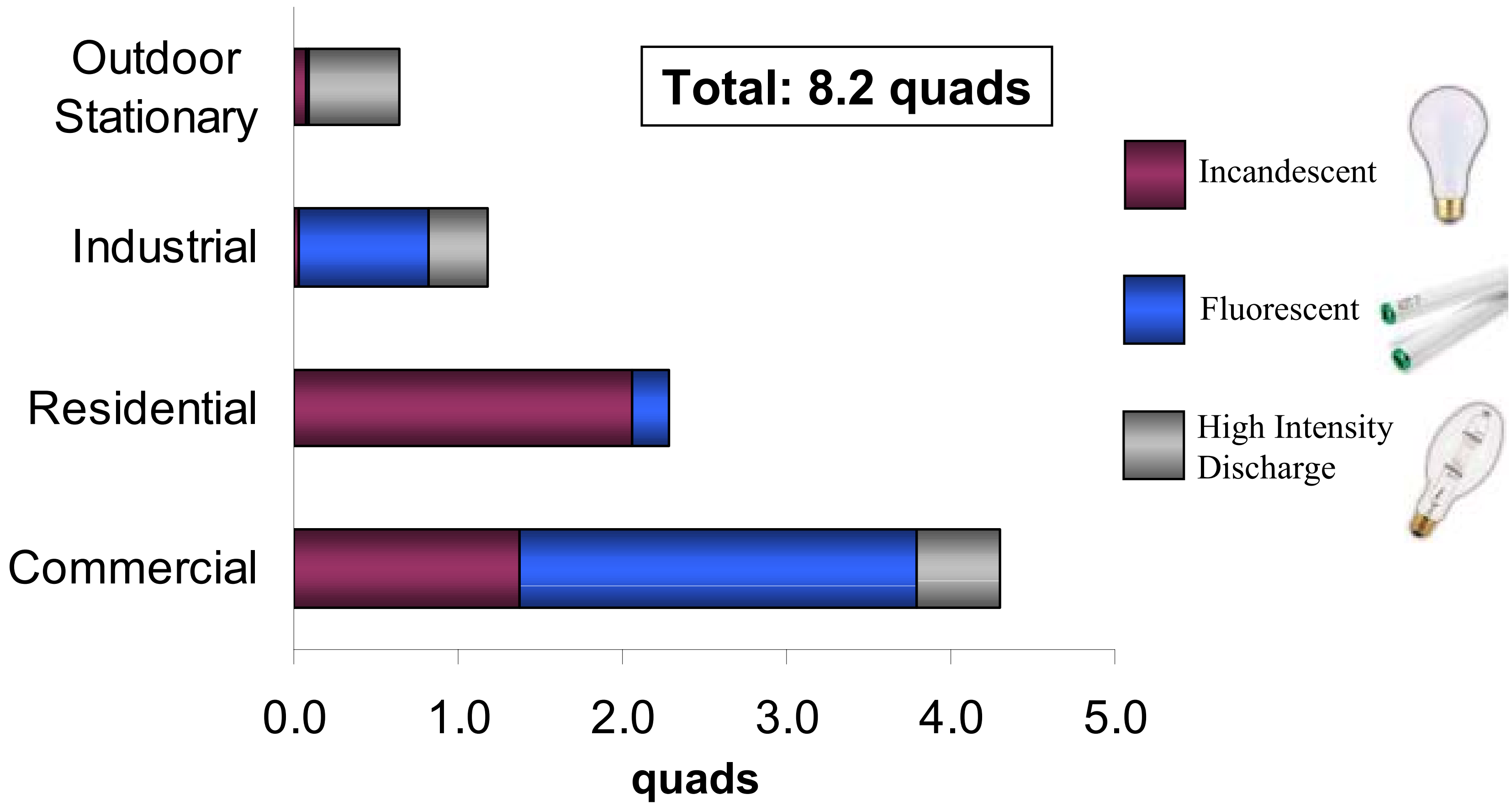


Quantity of primary energy consumed to provide electricity for lighting in each of these four sectors.

J. Brodrick, DOE

Source: U.S. Lighting Market Characterization Volume I — National Lighting Inventory and Energy Consumption Estimate, Navigant Consulting, September 2002.

Lighting Energy Use by Sector and Source



J. Brodrick, DOE

Source: U.S. Lighting Market Characterization Volume I — National Lighting Inventory and Energy Consumption Estimate, Navigant Consulting, September 2002.

Alternative, More Efficient Lighting Technologies:

Light Emitting Diodes (LEDs)

Organic Light Emitting Diodes (OLEDs)

LEDs: Point sources

OLEDs: Distributed Sources

Different Applications

Analysis in the DOE and OIDA:

Switching from incandescent and fluorescent lamps to LEDs and OLEDs will save 760 GW of electrical energy over 25 years.

These savings will reduce carbon emissions by 28 million tons annually and prevent the need for 133 new power stations (1000 MW each)

New lighting culture

Are OLEDs for Real?

DOE / OIDA OLED Roadmaping Process: 2000 - 2002

Conclusions:

No fundamental obstacles exist to achieve

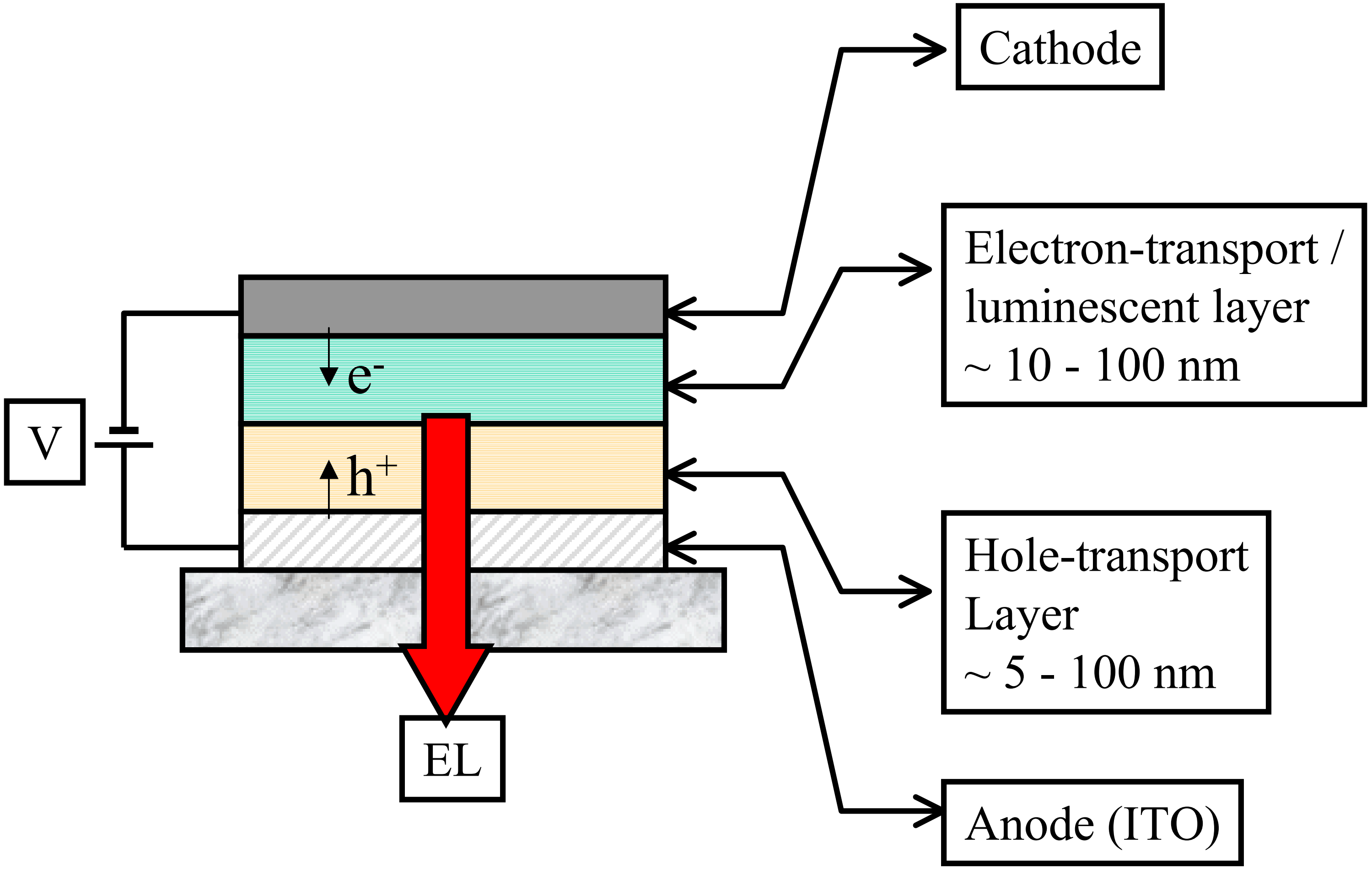
- **the desired power efficiency**
- **sufficient device life**
- **high quality white light**
- **low cost of manufacturing**

Feasibility demonstrated

However: significant challenges ahead

Principle of OLED Operation

Basic bi-layer OLED device structure



(Steve Van Slyke, Kodak)

Several Directions / Competing Systems:

Small molecules (vapor deposition, multiple layers, easy mixing with dopants…best "white")

Polymers (layers cast from solutions, simple devices, difficult to mix with dopants.…fluorescent.…less efficient, unless the fraction of excitons formed as singlets is increased to >> 60% (indirect evidence), or unless triplet emitters are used.

Fluorescent emitters (more stable, but less efficient. Polymers themselves may emit light - no need to use emitters

Phosphorescent emitters (more efficient - by a factor of ~ 4, but blue is difficult)

Polymers mixed with emissive nanoparticles (quantum dots). (New)

What Makes OLEDs Attractive:

* **Energy efficient:** Potentially:
  Ten times as efficient as incandescent lamps
  Twice as efficient as fluorescent lamps

* **Flexible, conformable to any shape and form**
  Freedom to produce sources of any shape or color tone will create radically new illumination culture

* **Extremely thin**
  Space savings (airplanes, tall buildings)

* **Inexpensive, if produced by roll-to-roll technique**

* **“Distributed” source. New paradigm in lighting**
  Panels, ceilings, partitions, large areas, fibers….

* **Environment-friendly**

* **Ultralight**

Electroluminescence

El. potential

Charge injection & migration

Recombination of charges

Excitation

Exciton migration

Light emission

Photovoltaics

El. potential

Charge separation

Exciton migration

Excitation

Light absorption

Photoconductivity

El. field

Charge separation

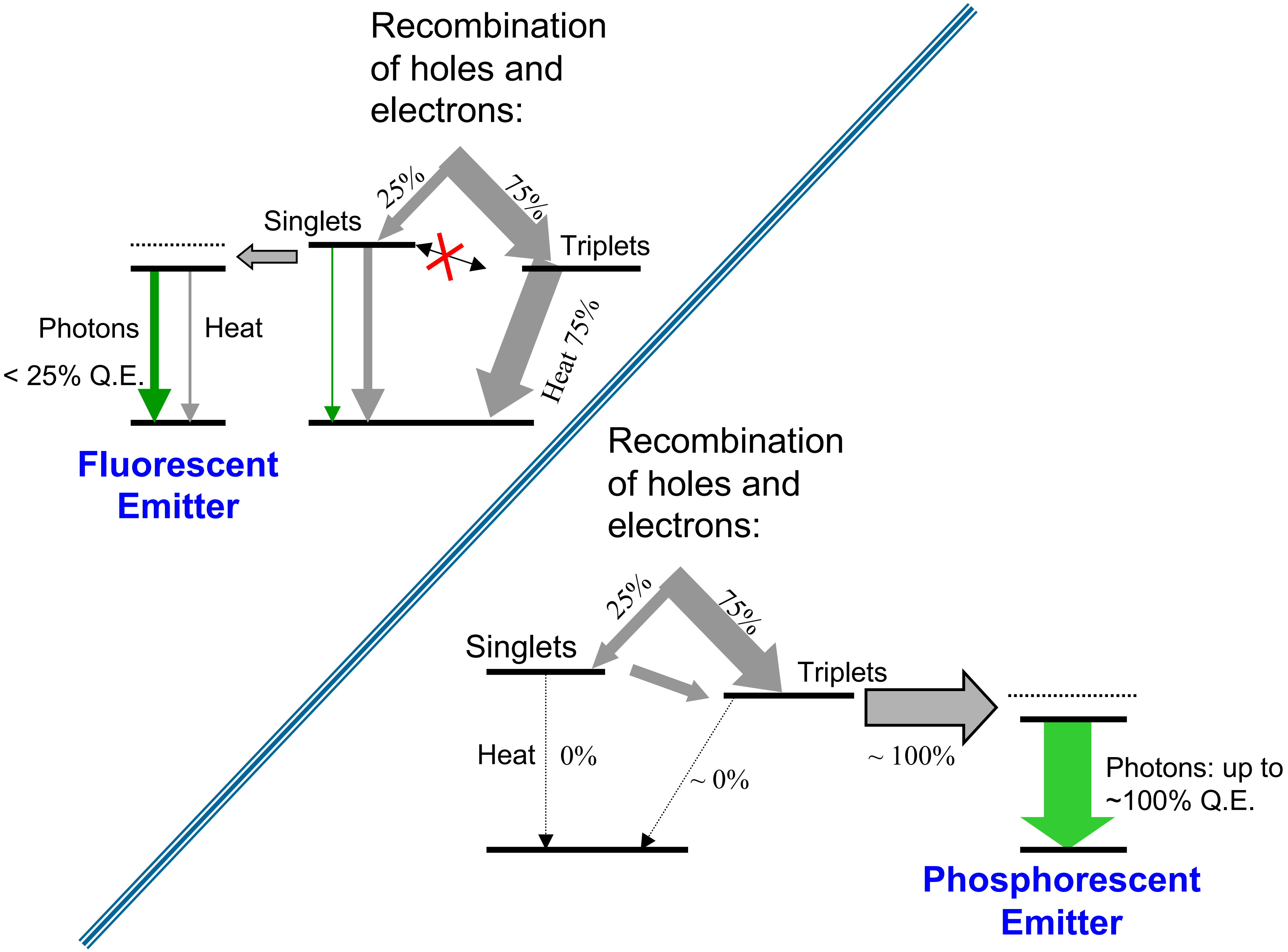
Exciton migration

Excitation

Light absorption

<u>Major issues</u>:

- Efficiency
- Life
- Manufacturing (cost)
- Infrastructure


Recombination
of holes and
electrons:
25%
75%
Singlets
Triplets
Photons
Heat
< 25% Q.E.
Heat 75%
Fluorescent
Emitter
Recombination
of holes and
electrons:
25%
75%
Singlets
Triplets
Heat
0%
~ 0%
~ 100%
Photons: up to
~100% Q.E.
Phosphorescent
Emitter

Issue: Power Efficiency

Incandescent (light bulbs)	10 - 20 lm/W
Fluorescent lamps	80 - 100 lm/W

Yellow - green polymeric OLEDs	20+ lm/W*	(at low A)
Green phosphorescent SM OLEDs	90 lm/W*	- " -
Other colors	5 - 40 lm/W*	- " -
White (not yet optimized)	~ 5 lm/W*	- " -
Internal quantum efficiency:	up to 100%	

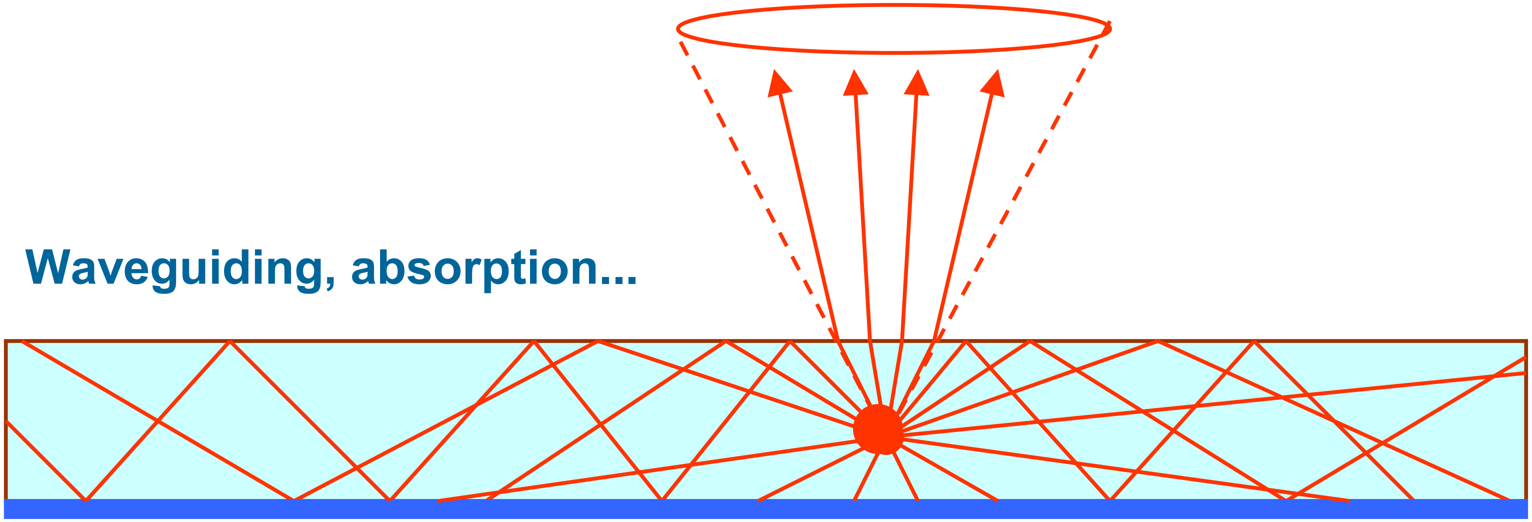
*) BEFORE ANY ATTEMPT WAS MADE TO INCREASE THE *EXTERNAL* QUANTUM EFFICIENCY!
2.5x Improvements already demonstrated.

Need an overall improvement of ~ 10 x to exceed fluorescent lamps.

Outcoupling:

Less than 20% of generated photons make it out of the device !

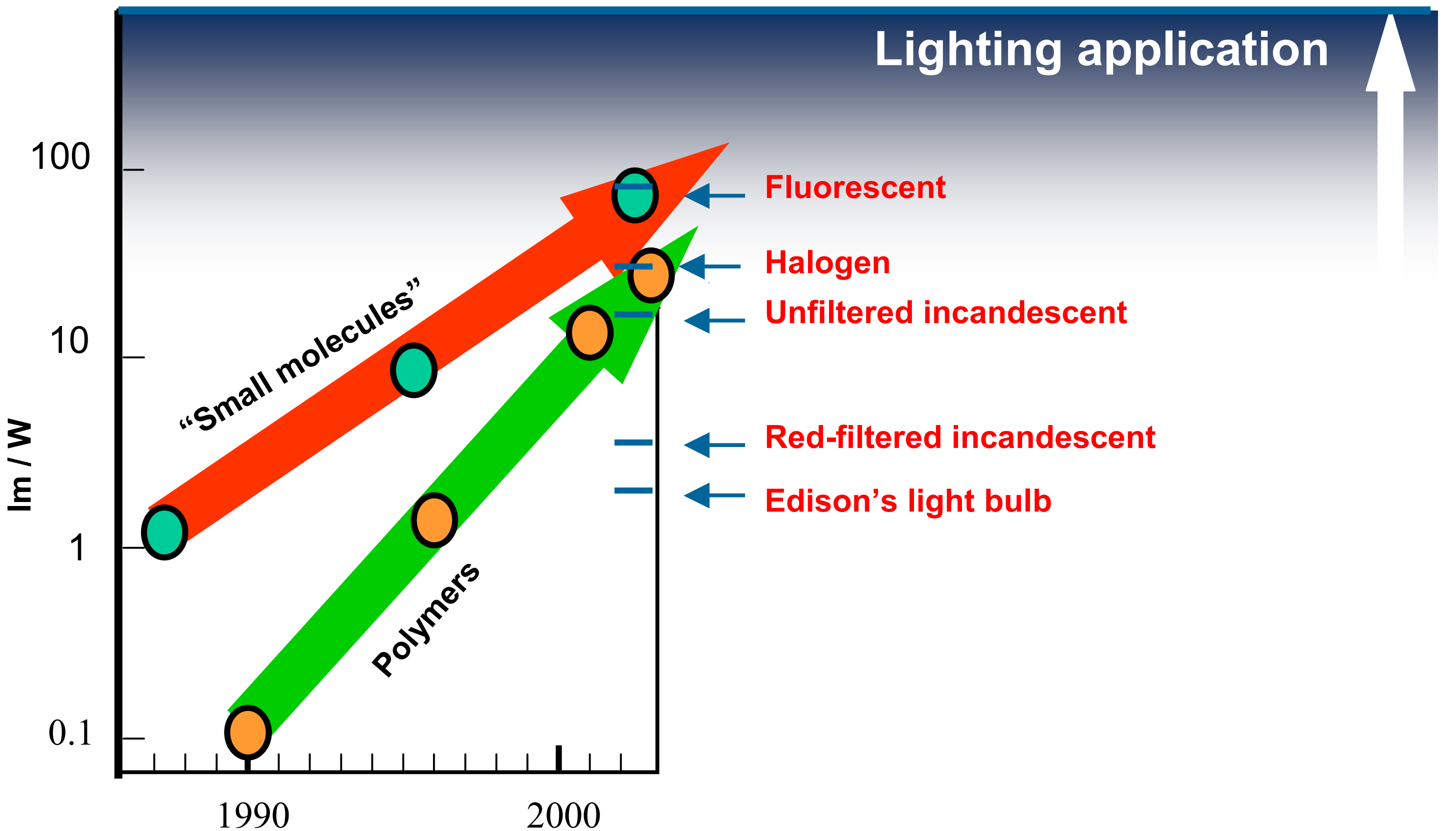
Waveguiding, absorption...



Ways to improve outcoupling:

Corrugated interfaces,
microlenses,
reflective microparticles….

Performance of OLEDs



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OLED Device Efficiency

$$W = V \times A$$

$$L = k_1 \times A$$

Goal: Minimize A

Maximize k_1 (efficiencies):

- all charge carriers produce excitons (materials, device)
- high internal quantum efficiency (materials)
- high external quantum efficiency (device architecture)

Minimize W - reduce V:

- thinner layers (device architecture)
- lower injection barriers (materials)

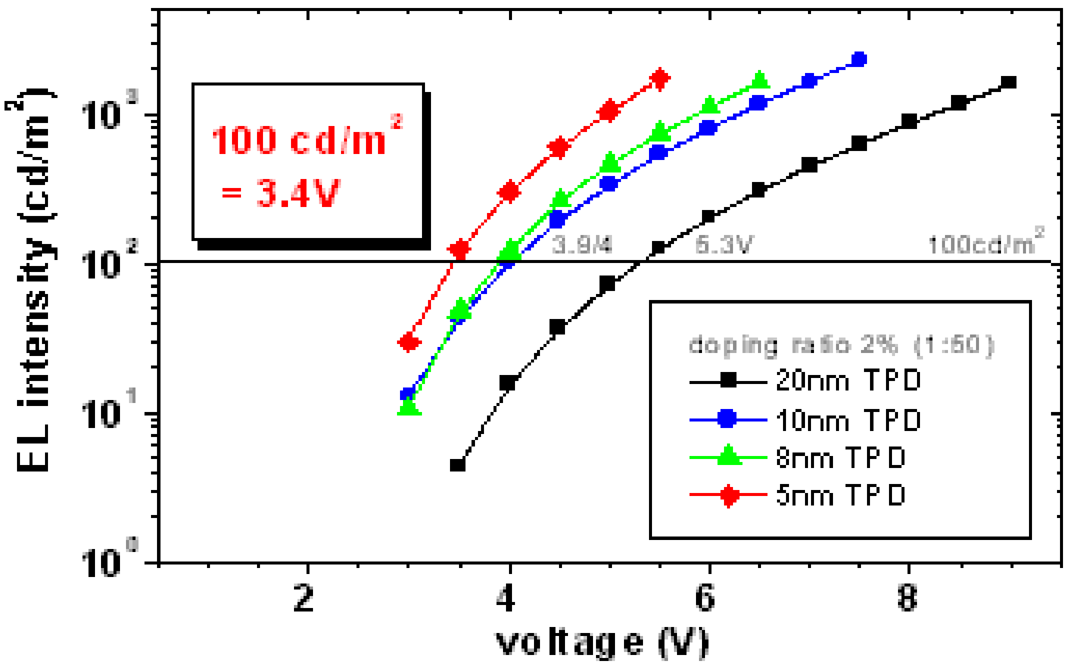
Ways to Improve OLED Device Efficiency

Expected improvement

- **Thinner layers, reduction of injection barriers**
  lower voltage to get the same current (luminance); control of interfaces; doping
  W = V x A .... **2 - 4 x**

- **Improving light extraction efficiency**, e.g. by using microlenses on the surface, etc.
  An improvement by a factor of 2.5 was already demonstrated. .... **3 - 4 x**

- **Extensive optimization of many parameters**:
  Introduction of blocking layers
  Control of physics of excitons
  Exciton blockers (molecules)
  New more efficient emitters, etc.................... **2 - 6 x**



For a constant driving current (= constant light output), making the HTL thinner enables voltage reduction - the input watts decrease.

OLED EFFICIENCY ROLL-OFF DUE TO:

- Exciton-exciton quenching: $T_1 + T_1 \longrightarrow S_0 + S_1$

  Baldo *et al*., Phys. Rev. B 62, 10967 (2000)

- Polaron-exciton quenching: S_1 or $T_1 \xrightarrow{X^{\oplus/\ominus}} S_0$

  Young *et al*., Appl. Phys. Lett. 80, 874 (2002).

- Exciton dissociation: S_1 or $T_1 \xrightarrow{\text{E-field}} X^{\oplus} + X^{\ominus}$

  Szmytkowski et al., Appl. Phys. Lett. 80, 1465 (2002)

- Heating

→ Not Unique to phosphorescent devices!

Issue: Operational Life of OLEDs

- The rate of degradation of OLEDs is approximately proportional to the driving current (luminance)
- Displays operate at 50 - 300 cd/m^2
  Life (to 50% luminance) of 10,000 hrs achieved for all colors
- Lighting applications require ~ 1,000 cd/m^2 (= 5 x brighter = 5X faster degradation)
- Need: 20,000 hrs with < 20% decrease in luminance

Needs 20 x improvement

Latest Performance of PHOLEDs

Color	Green	Red	Blue
Peak Wavelength	510	620	460
CIE - x	0.28	0.65	0.14
CIE - y	0.64	0.35	0.23
Luminance Efficiency (cd/A @ 1mA / cm^2)	24	12	9
Lifetime (to 50%)	10,000 hrs. @ 600 cd/m^2 ↓ 7,000 hrs. @900 cd/m^2	15,000 hrs. @300 cd/m^2 ↓ 5,000 hrs. @900 cd/m^2	>1,000 hrs. @300 cd/m^2 ↓ >300 hrs. @900 cd/m^2

(M. Hack, Universal Display Corporation, INTERTECH 11/02)

Latest Data on Lifetime of Polymeric OLEDs

Color	Green	Red	Blue
Measurement, hrs. (conditions)	2,400 (80°C, 400 cd/m^2) ↓	4,800 (80°C, 400 cd/m^2) ↓	
Extrapolated values	25,000 (RT, 400 cd/m^2) ↓ 10,000 (RT 900 cd/m^2)	50,000 (RT, 400 cd/m^2) ↓ 20,000 (RT 900 cd/m^2)	8,000 (RT, 400 cd/m^2) ↓ 3,000 (RT 900 cd/m^2)

(D. Fyfe, Cambridge Display Technology, INTERTECH 11/02)

Ways to Improve Operational & Shelf Life of OLEDs

	Expected improvement
* Extreme "dry" and 0_2- free fabrication conditions	1.1 - 1.5 x
* Encapsulation. Methods already known, but not typically used in lab experiments.	up to 20 x
* Selection of more stable emitters (empirical)	1.5 - 10 x
* Understanding and control of photophysical and photochemical phenomena. Photochemical degradation suspected.	3 x
* Understanding and control of interfacial and electrode chemistry / electrochemistry	< 1.5 x
* Feedback controls - increase of driving current as light output begins to decrease...............	1.5 - 5 x

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Getting White Light from OLEDs:

* Mixing basic colors (two or more)
  * *Single layer*
  * *Multiple layers*
* Mixing colors obtained in separate regions - dots, strips…
* Using monomer - excimer phosphorescence
  * *Single dopant*
  * *Two dopants*
* Coupling of a blue emitter and down-conversion phosphors
* (Nanoparticles as emitters) (*New*)

Goal: Blackbody T= 6300K

0.32, 0.32 — Approximated many times

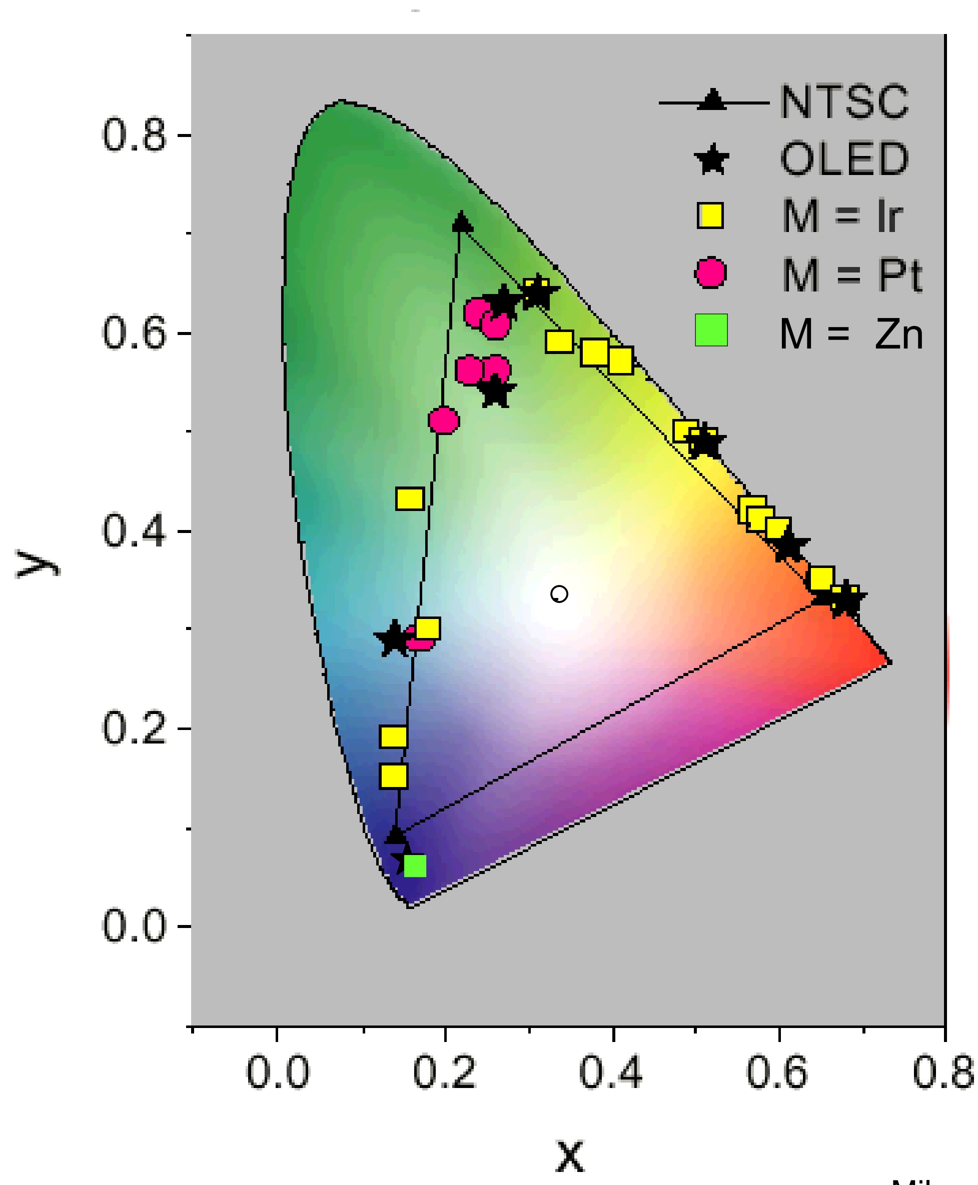
CRI > 80 — First four: > 80, highest reported: 93

[Chromaticity Diagram of Phosphorescent OLEDs (PHOLEDs).]

Phosphorescent emitters: Unlimited design possibilities.

(Courtesy Universal Display Corporation, Princeton U, USC, April 2002);

US Pat. 6,458,475 (10/02)



Formidable Challenges Ahead

Design phase:	***Issues***
Emitters:	**Color (blue)** **Stability** **High quantum efficiency**
Electrodes:	**Injection barriers** **Insufficient conductivity** **Transparency**
Device Architecture:	**Number of layers** **Thicknesses, no pinholes** **Charge & exciton blockers** **Encapsulation** **Surface treatment, etc.**
Substrates:	**Surface defects** **Impurities** **Stability at high T**

Formidable Challenges Ahead

Manufacturing:

Continuous roll-to-roll deposition. Large areas

- Defect free layers
- Uniform
- Extremely thin (~ 10 nm)
- Multiple layers - without intermixing

Encapsulation

- Protection against moisture (CO_2, O_2)
- Pinhole - free
- Transparent to light

Surface patterning to increase external quantum efficiency

Methods of packaging

- Slicing
- Connecting to conduits, etc.

Formidable Challenges Ahead

Infrastructure

Connection to el. network. “Plumbing”

Power distribution

Low V, High A *(Photovoltaics: same problem?)*

120 V (AC) → 3 - 4 V (DC) (where?)

New building standards

Long - Term Research and Development Issues

* Design of stable emitters (particularly ***blue***). Related photophysics
* Light extraction (outcoupling)
* Device modeling and optimization
* Development of stable, highly conductive anodes and cathodes
* Control of interfaces to minimize injection barriers
* Understanding of degradation mechanisms
* Methods to produce white light
* Continuous large area deposition
* Protection against ambients
* Manufacturing research to identify cost effective methods of production
* Infrastructure and powering of OLEDs
* New approaches: Nanoparticles

CONCLUSIONS

* OLEDs ***will*** **be used as source of light for general illumination**

* **There are no fundamental obstacles in the way**

but:

* **Many challenges lay ahead**

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Milan Stolka