

Introduction

Scientific research in the area of semiconducting organic materials as the active substance in light emitting diodes (LEDs) has increased immensely during the last four decades. Organic semiconductors was first reported in the 60:s and then the materials where only considered to be merely a scientific curiosity. (They are named organic because they consist primarily of carbon, hydrogen and oxygen.). However when it was recognized in the eighties that many of them are photoconductive under visible light, industrial interests were attracted. Many major electronic companies, such as Philips and Pioneer, are today investing a considerable amount of money in the science of organic electronic and optoelectronic devices. The major reason for the big attention to these devices is that they possibly could be much more efficient than todays components when it comes to power consumption and produced light. Common light emitters today, Light Emitting Diodes (LEDs) and ordinary light bulbs consume more power than organic diodes do. And the strive to decrease power consumption is always something of matter. Other reasons for the industrial attention are i.e. that eventually organic full color displays will replace todays liquid crystal displays (LCDs) used in laptop computers and may even one day replace our ordinary CRT-screens.

Organic light-emitting devices (OLEDs) operate on the principle of converting electrical energy into light, a phenomenon known as electroluminescence. They exploit the properties of certain organic materials which emit light when an electric current passes through them. In its simplest form, an OLED consists of a layer of this luminescent material sandwiched between two electrodes. When an electric current is passed between the electrodes, through the organic layer, light is emitted with a color that depends on the particular material used. In order to observe the light emitted by an OLED, at least one of the electrodes must be transparent.

When OLEDs are used as pixels in flat panel displays they have some advantages over backlit active-matrix LCD displays - greater viewing angle, lighter weight, and quicker response. Since only the part of the display that is actually lit up consumes power, the most efficient OLEDs available today use less power.

Based on these advantages, OLEDs have been proposed for a wide range of display applications including magnified microdisplays, wearable, head-mounted computers, digital cameras, personal digital assistants, smart pagers, virtual reality games, and mobile phones as well as medical, automotive, and other industrial applications.

OLED Versus LED

Electronically, OLED is similar to old-fashioned LEDs -- put a low voltage across them and they glow. But that's as far as the similarity goes: instead of being made out of semiconducting metals, OLEDs are made from polymers, plastics or other carbon-containing compounds. These can be made very cheaply and turned into devices without all the expensive palaver that goes with semiconductor fabrication.

Light-emitting diodes, based upon semiconductors such as Gallium Arsenide, Gallium Phosphide, and, most recently, Gallium Nitride, have been around since the late '50s. They are mostly used as indicator lamps, although they were used in calculators before liquid crystals, and are used in large advertising signs, where they are valued for very long life and high brightness. Such crystalline LEDs are not inexpensive, and it is very difficult to integrate them into small high-resolution displays.

The operation of an LED is based upon the fact that semiconductors can be of two types, p-type or n-type, depending upon whether dopants pull electrons out of the crystal, forming "holes", or add electrons. An LED is formed when p-type and n-type materials are joined. When a voltage is applied, causing electrons to flow through the structure, electrons flow into the p-type material, and holes flow into the n-type material. An electron-hole combination is unstable; there is too much potential energy to be released. As a result, they combine and release the energy in the form of light. This can be a very efficient way to convert electricity to light.

There is a wide class of organic compounds, called conjugated organics or conjugated polymers, which have many of the characteristics of semiconductors. They have energy gaps of about the same magnitude, they are poor conductors without dopants, and they can be doped to conduct by electrons (n-type) or holes (p-type).

Initially, these materials were used as photoconductors, to replace inorganic semiconductor photoconductors, such as selenium, in copiers. About fifteen years ago it was discovered that, just as with crystalline semiconductors, p-type and n-type organic materials can be combined to make light-emitting diodes whereby a current passing through a simple layered structure produces visible light with high efficiency.

Since light-emitting diodes, as their name suggests, actually generate their own light while using very little battery power, they have long been viewed as an obviously better way to create displays. Unfortunately, while conventional L.E.D.'s work well in giant screens and advertising displays like those in Times Square, they cannot easily be used to create small, high-resolution screens for portable computers.

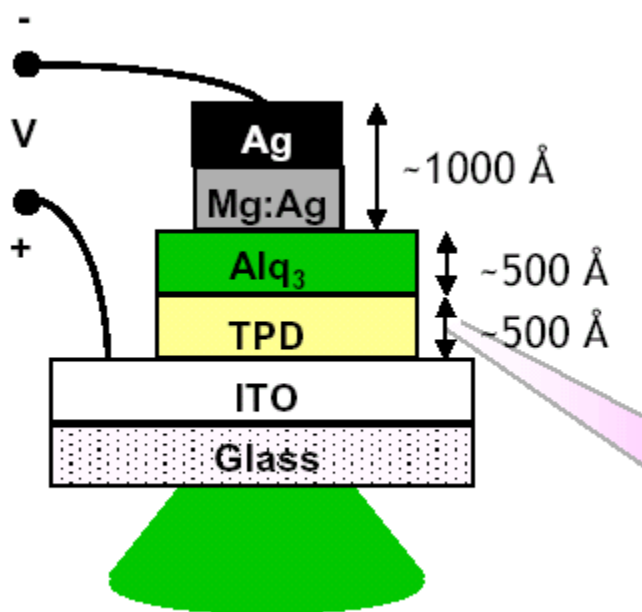
OLED is an emissive display technology based on thin organic light-emitting films. Like conventional inorganic light emitting diodes (LED), OLED requires a low-drive voltage to produce bright visible light. But unlike discrete LEDs, which have crystalline origins, thin film-based OLEDs have area emitters that can easily be patterned to produce flat-panel displays. Because OLEDs are self-luminous, backlights are not required as in liquid-crystal displays (LCDs). OLEDs have very low power requirements and are thin, bright and efficient.

Because crystalline order is not required, organic materials, both molecular and polymeric, can be deposited far more cheaply than the inorganic semiconductors of conventional LED's. Patterning is also easier, and may even be accomplished by techniques borrowed from the printing industry. Displays can be prepared on flexible, transparent substrates such as plastic. These characteristics form the basis for a display technology that can eventually replace even paper, providing the same resolution and reading comfort in a long-lived, fully reusable (and eventually recyclable) digital medium.

Also OLEDs are much more efficient than today's components when it comes to power consumption and produced light. Common light emitters today, Light Emitting Diodes (LEDs) and ordinary light bulbs consume more power. To tell something about the efficiency of components we will use the concept of Quantum Efficiency (QE), which is defined as the relation between photons produced and electrons injected. To achieve a high QE for a light bulb it would be necessary to change the relation between produced heat and produced light. To increase the QE for a LED it is necessary to limit the absorption of the photons produced. It has been generally observed that organic devices can and will produce high quantum efficiencies than organic diodes do.

The operation of an organic light emitting diode

The organic light emitting diode (OLED) is a p-n diode, in which charge-carriers (e-h pairs) recombine to emit photons in an organic layer. The thickness of this layer is approximately 100 nm (experiments have shown that 70 nm is an optimal thickness). When an electron and a hole recombine, an excited state called an exciton is formed. Depending on the spin of the e-h pair, the exciton is either a singlet or a triplet. An electron can have two different spins, spin up and spin down. When the spin of two particles is the same, they are said to be in a spin-paired, or a triplet state, and when the spin is opposite they are in a spin-paired singlet state.



On the average, one singlet and three triplets are formed for every four electron-hole pairs, and this is a big inefficiency in the operation of the diodes. A singlet state decays very quickly, within a few nanoseconds, and thereby emits a photon in a process called fluorescence. A triplet state, however, is much more long-lived (1 ms - 1 s), and generally just produce heat. One method of improving the performance is to add a phosphorescent material to one of the layers in the OLED. This is done by adding a

heavy metal such as iridium or platinum. The exciton can then transfer its energy to a phosphorescent molecule which in turn emits a photon. It is however a problem that few phosphorescent materials are efficient emitters at room temperature.

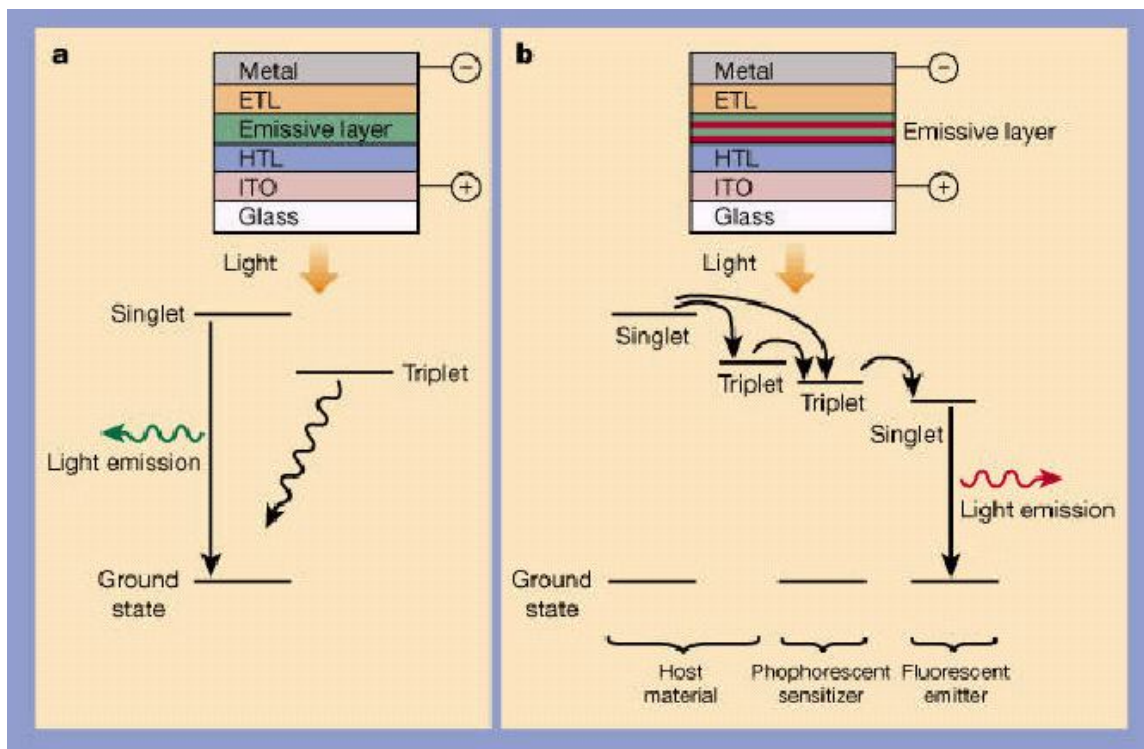
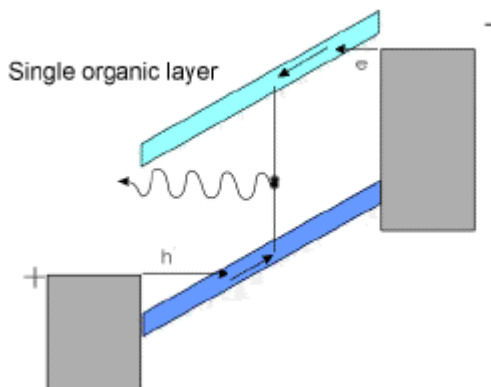


Figure 1: Two different ways of decay.

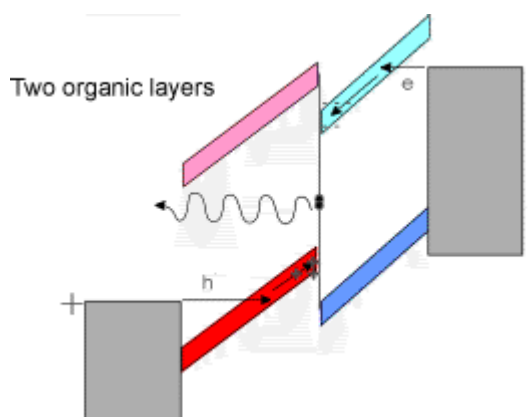
There have been devices manufactured which transform both singlet and triplet states in a host to a singlet state in the fluorescent dye. This is done by using a phosphorescent compound which both the singlets and triplets transfer their energy to, after which the compound transfers its energy to a fluorescent material which then emits light.

Using one organic layer has some problems associated with it. The electrodes energy levels have to be matched very closely, otherwise the electron and hole currents will not be properly balanced. This leads to a waste in energy since charges can then pass the entire structure without recombining, and this lowers the efficiency of the device.

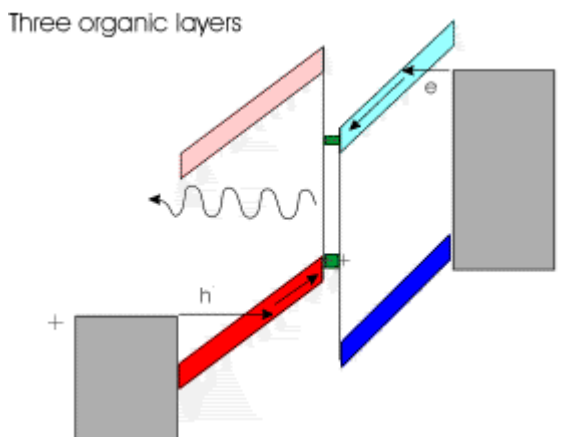
With two organic layers, the situation improves dramatically. Now the different layers can be optimized for the electrons and holes respectively. The charges are blocked at the interface of the materials, and “waits” there for a “partner”.



Considerably better balance can be achieved by using two organic layers one of which is matched to the anode and transports holes with the other optimized for electron injection and transport. Each sign of charge is blocked at the interface between the two organic layers and tend to "wait" there until a partner is found. Recombination therefore occurs with the exciton forming in the organic material with the lower energy gap. The fact that it forms near the interface is also beneficial in preventing quenching of the luminescence that can occur when the exciton is near one of the electrodes.



Another improvement is to introduce a third material specifically chosen for its luminescent efficiency. Now the three organic materials can be separately optimized for electron transport, for hole transport and for luminescence.



Multilayer organic light emitting diodes

The principle of operation of organic light emitting diodes (OLEDs) is similar to that of inorganic light emitting diodes (LEDs). Holes and electrons are injected from opposite contacts into the organic layer sequence and transported to the emitter layer. Recombination leads to the formation of singlet excitons that decay radiatively. In more detail, electroluminescence of organic thin film devices can be divided into five processes that are important for device operation:

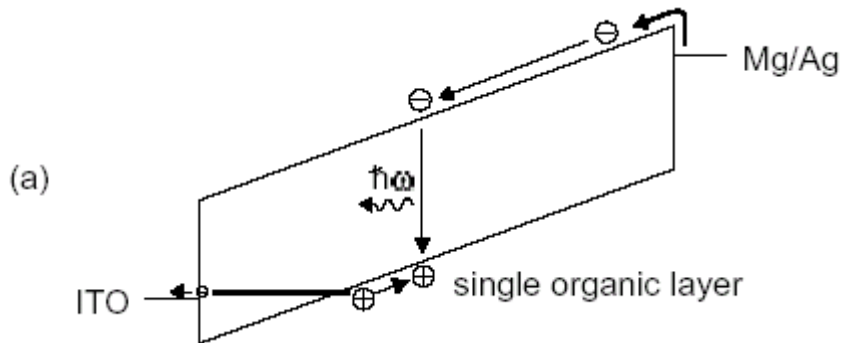
(a) Injection: Electrons are injected from a low work function metal contact, e. g. Ca or Mg. The latter is usually chosen for reasons of stability. A wide-gap transparent indium-tin-oxide (ITO) or polyaniline thin film is used for hole injection. In addition, the efficiency of carrier injection can be improved by choosing organic hole and electron injection layers with a low HOMO (high occupied molecular orbital) or high LUMO (lowest unoccupied molecular orbital) level, respectively.

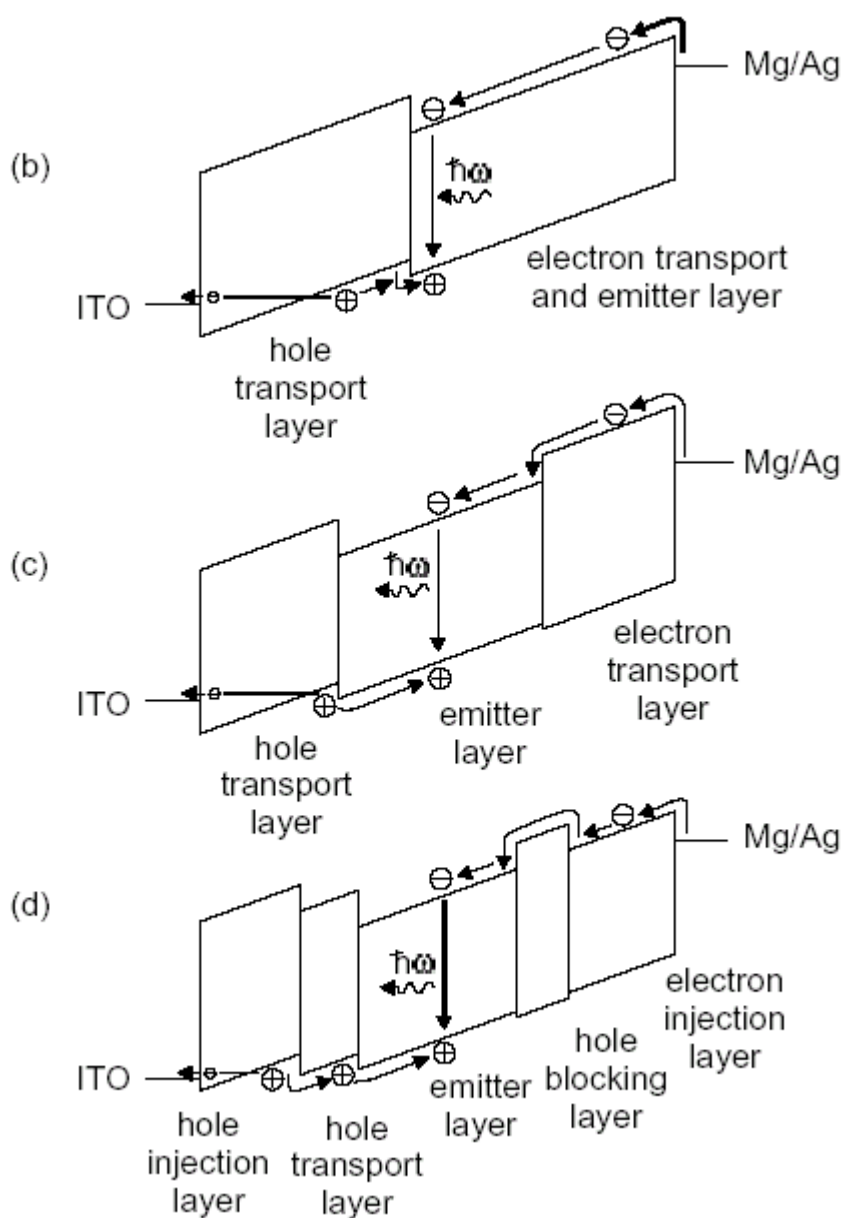
(b) Transport: In contrast to inorganic semiconductors, high p- or n-conducting organic thin films can only rarely be obtained by doping. Therefore, preferentially hole or electron transporting organic compounds with sufficient mobility have to be used to transport the charge carriers to the re-combination site. Since carriers of opposite polarity

also migrate to some extent, a minimum thickness is necessary to prevent non-radiative recombination at the opposite contact. Thin electron or hole blocking layers can be inserted to improve the selective carrier transport.

(c) Recombination: The efficiency of electron-hole recombination leading to the creation of singlet excitons is mainly influenced by the overlap of electron and hole densities that originate from carrier injection into the emitter layer. Recombination of filled traps and free carriers may also attribute to the formation of excited states. Energy barriers for electrons and holes to both sides of the emitter layer allow to spatially confine and improve the recombination process.

(d) Migration and (e) decay: Singlet excitons will migrate with an average diffusion length of about 20 nm followed by a radiative or non-radiative decay. Embedding the emitter layer into transport layers with higher singlet excitation energies leads to a confinement of the singlet excitons and avoids non-radiative decay paths. Doping of the emitter layer with organic dye molecules allows to transfer energy from the host to the guest molecule in order to tune the emission wavelength or to increase the luminous efficiency.

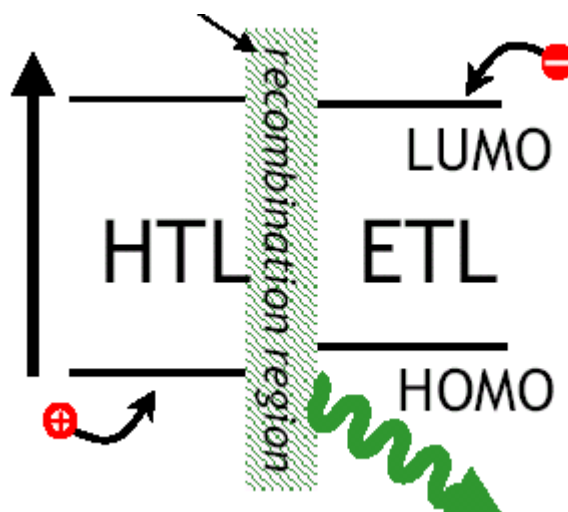




Layer sequences and energy level diagrams for OLEDs with (a) single layer, (b) single heterostructure, (c) double heterostructure, and (d) multilayer structure with separate hole and electron injection and transport layers.

When biased, charge is injected into the highest occupied molecular orbital (HOMO) at the anode (positive), and the lowest unoccupied molecular orbital (LUMO) at

the cathode (negative), and these injected charges (referred to as “holes” and “electrons,” respectively) migrate in the applied field until two charges of opposite polarity encounter each other, at which point they annihilate and produce a radiative state emitting photons with energy $hf = E_g$. The energy gap is the difference between the HOMO and LUMO level of the emitting layer, and it is largely responsible for the observed color of the light.



Factors Influencing Performance

Various factors influence the quality of the OLED, including the choice of materials, thickness, geometry, purity of samples, and contamination from air or other sources. The factors that are most responsible for the quality are the choice of materials in the ETL and HTL layer. Different combinations will emit different colors and have different lifetimes.

The two most important factors are electron mobility and energy levels of the highest unoccupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO). Materials are generally chosen so that the energy levels of the HOMO and LUMO levels “match” as electrons and holes travel from one side to another.

HOMO/LUMO Levels

As electrons travel from the cathode, they must jump from the LUMO of one material to the LUMO of the next material. A small energy gap enhances the conditions for electron flow. The same is true for the holes as they travel in the opposite direction. The need to facilitate electron flow by reducing the energy gaps between the LUMO-LUMO levels and HOMO-HOMO levels of the materials in sequence is the major reason for the use of more than one material layer in the HTL and ETL. The energy gap between successive levels is on the order 0.2 eV. The positron falls into consecutively lower HOMO energy levels, while the electron falls into consecutively lower LUMO levels. When they meet, they emit a quantum of light or travel as an exciton.

Materials are chosen so that the energy levels “match” in going from one level to another. In general, the absolute value of the energy level increases in going from the anode to the HTL and in going from the cathode to the ETL (including any layers in between). Minimizing the jump in the HOMO or LUMO energy from one layer to another greatly facilitates the motion of electrons and holes (positrons). Often buffer

layers are placed between two layers (between the cathode and ETL). The buffers work by the same mechanism, aiding electron flow.

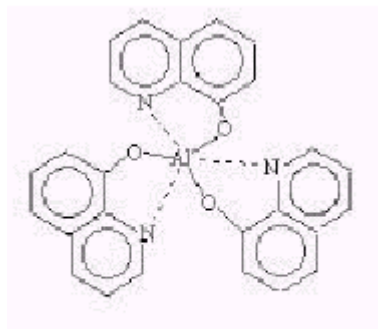
Hole and Electron Mobility

Another major factor influencing performance is hole and electron mobility. The low electron mobility of most organic materials prevents their use as materials in an ETL layer.

The materials chosen for the HTL and ETL layers are organic materials that contain several hexagonal and/or pentagonal π -conjugated rings. The success of their performance is due to the behavior of the π -bonds. They behave as semiconductors, due to the small energy gap between the highest unoccupied π -orbital and the lowest unoccupied π -orbital. Within the ring structures, the π -orbitals overlap one another. This overlap of the adjacent π -orbital wave functions makes the electrons relatively delocalized, i.e., capable of mobility, a property contributing to their performance as semiconductors.

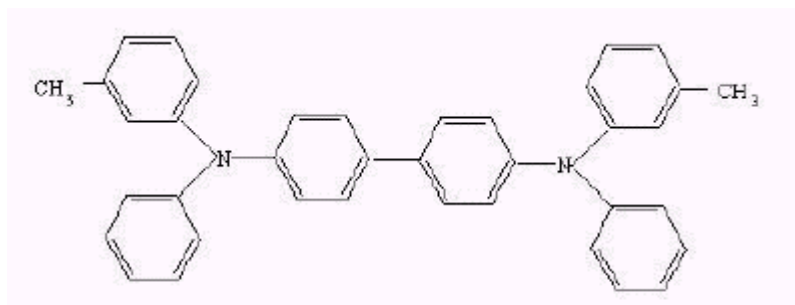
In traditional OLEDs, the light emission is based on fluorescence, a transition from a singlet excited state of a material. According to theoretical and experimental estimation, the upper limit of efficiency of an OLED doped with fluorescent material, is approximately 25%.

With the electro phosphorescent materials used as a dopant, which exploits both singlet and triplet excited states, this upper limit is virtually eliminated. Equipped with the potential of 100% efficiency.



Alq₃¹²

Electron Transporting Materials

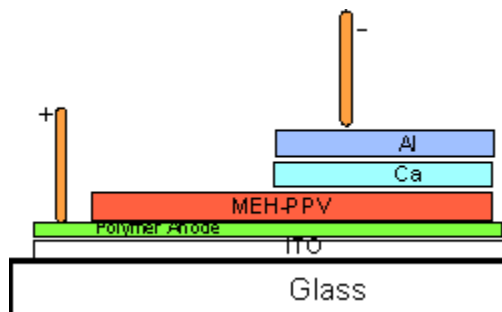


TPD¹⁰

Hole Transporting Materials

OLED Fabrication

OLEDs are typically fabricated on a transparent substrate on which the first electrode (usually indium-tin-oxide which is both transparent and conductive) is first deposited. Then one or more organic layers are coated by either thermal evaporation in the case of small organic dye molecules, or spin coating of polymers. In addition to the luminescent material itself, other organic layers may be used to enhance injection and transport of electrons and/or holes. The total thickness of the organic layers is of order 100 nm. Lastly, the metal cathode (such as magnesium-silver alloy, lithium-aluminum or calcium) is evaporated on top. These metals are chosen for their low workfunctions in order that they provide efficient injection of electrons. The two electrodes add perhaps 200 nm more to the total thickness of the device. Therefore the overall thickness (and weight) of the structure is mostly due to the substrate itself.



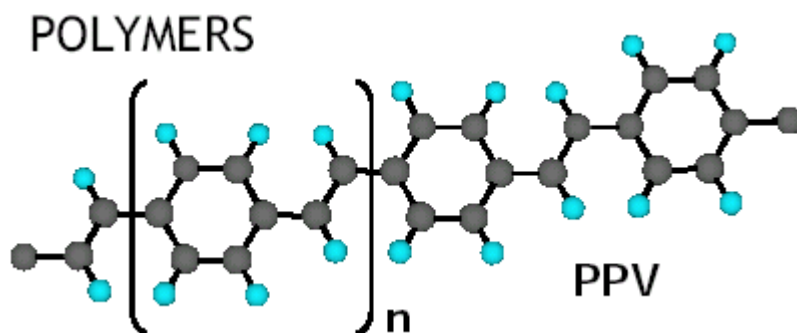
The technology, Organic Vapor Phase Deposition (OVPD), can enable a low cost, precise, high throughput process for fabricating OLEDs.

The OVPD production process utilizes a carrier gas stream in a hot walled reactor at very low pressure to precisely deposit the thin layers of organic materials used in OLED displays. Conventional OLED fabrication equipment evaporates the organic molecules at high temperature and pressure. OVPD offers the ability to precisely control the multi-source deposition required for full-color OLED displays. The OVPD design should also be adaptable to the rapid, uniform deposition of organics on large-area substrates and for roll-to-roll processing.

Polymer LEDs

Polymers are giant molecules consisting of linked sequences of identical chemical units that are entangled in a spaghetti-like way. It has been shown that a number of polymeric materials are suitable for use as organic semiconducting materials in light-emitting diodes. In the last ten years, polymers have also been found to have optical and electrical properties that make them functionally suitable for replacing materials such as glass and silicon, with their inherent advantages of being less expensive and more easily processed. Functional polymers are used in the manufacturing of light-emitting devices known as PolyLEDs. Their application in segmented and high-resolution matrix displays has a tremendous business potential.

More recently, light emitting diode using polymers, specifically poly-paraphenylene vinylene (PPV) as the emitter was developed. This device is variously called a polymer LED (PLED) or a light emitting polymer (LEP). Polymer devices employing polyfluorene-based materials have achieved efficiencies at least as good as those of molecular OLEDs, but as yet their lifetimes are inferior.



The stated advantage of the polymer devices is the ability to spin the layers on and, in some cases, to pattern the films with photolithography. Molecular films, on the other hand, are typically soluble in both water and common organic solvents, so

patterning with conventional photolithographic techniques is not feasible. This creates a real challenge for achieving high resolution simple matrix displays and displays with fine stripes of different emitters for full color displays.

Polymer materials can easily be processed into large-area thin films using simple and inexpensive technology. The polymers are lightweight and flexible, and many of their properties can be adjusted to suit specific needs.

Polymer LEDs have several inherent properties which afford unique possibilities. For example:

- all colours of the visible spectrum are available
- high brightness is achieved at low drive voltages/current densities
- there is no viewing angle dependence
- operating lifetimes exceed 1000 hours

Further, small pixelated alphanumeric displays based on these polymer LEDs can be made by structuring the polymer material and the electrodes.

PolyLED Displays

The Polymer Light Emitting Diode (PLED) Display is a thin, lightweight emissive alternative to a conventional backlit LCD display. The device is a simple sandwich-type structure, the active polymer layer lies between a semi-transparent column anode and a back row cathode. A protective cap keeps the display sealed against environmental damage.

The displays utilize the unique semiconductor properties of conjugated polymer chains. The polymer chains conduct in one dimension with weak link transport between chains. It is useful to think of the conduction properties of polymers as semiconductor-like, with an energy gap of roughly 2V. By matching the energy injection levels for the holes and electrons, a simple diode can be formed by sandwiching the polymer between transparent metal anode and cathode. Above the threshold voltage, recombination causes uniform emission of light throughout the entire active region. To create an addressable display, the anodes and cathodes are structured in a grid array pattern.

A PLED display consists of a thin layer of light emitting polymer sandwiched between two sets of electrodes, which are arranged perpendicular to one another. When a low-voltage DC bias is applied between a row and column electrode, the pixel defined at their intersection is turned on, and light is emitted. To make a display show meaningful information, a whole row of pixels is active (for a short time), and this row is swept down the display so that persistence of vision gives the impression of a full screen image. This type of drive scheme is called “Passive Addressing” and is simple and easy to implement for low-cost displays of modest size.

Performance

Compared to other display techniques, PolyLED displays provide more homogeneous illumination, are brighter and show more contrast, operate at lower voltages and can be looked at from all angles.

The display efficiency (in cd/A) remains high (above 10 cd/A) and fairly constant even at the high peak luminance required for passively addressed displays.

The DC operating voltage means that the devices are less subject to electromagnetic interference problems are less of a problem as compared to many other display types that are driven by AC voltages. Moreover, compared to a standard LCD

with a conventional backlight, PolyLED displays also consume considerably less power – thereby making them eminently suitable for mobile display applications such as telephones and handheld computers.

One of the original problems that had to be solved was the short lifetime of devices. It was soon found out that the major problem was the sensitivity of the device to water and oxygen at the interfaces in the structure of the polymer and metal sandwich. We therefore tried several packaging methods, leading to the development of a package with a water- and oxygen-absorbing getter inside. It is now possible to seal the devices so thoroughly that water and oxygen molecule penetration is no longer a problem, and indeed some devices are still running after 35'000 hours of continuous operation!

One of the advantages of the PolyLED technology is that the polymers are dispensed onto a substrate using standard spin-coating techniques. To move to full-colour, however, the different light-emitting polymers must be placed in a regular fashion in different pixels on the display. This means that the spin-coating method, which coats an entire substrate with one particular polymer, cannot be used and that a more controlled dispensing of the polymer solutions is required. High-precision inkjet technology has therefore been used for these functional polymers, and is currently being tested as the most likely candidate for low-cost manufacturing of full-colour displays on large substrates.

The intrinsic response speed of a single pixel under ideal test conditions – not limited by RC constants, is less than 50 nanoseconds (on/off time). In a display the actual switching response speed is determined by RC time-constants, but is still sub microsecond. Unlike liquid crystal displays, the switching speed remains high even at low temperatures.

Organic displays

Organic light emitting diodes (OLEDs) are attractive for the use in lightweight, low-cost flat panel displays. Multilayer devices grown by the organic molecular beam deposition (OMBD) technique achieve bright electroluminescent emission in the entire visible spectral region. Turn-on voltages below 10 V, luminance of about 10^4 cd/m², and internal quantum efficiencies exceeding 5 % are satisfactory for emissive displays.

The current color flat-panel displays do everything backward. First, the screen is lighted to its full brightness by a battery-draining lamp. Then a series of color filters and tiny liquid crystal displays, or L.C.D.'s, block most of that light to create on-screen images. Since light-emitting diodes, as their name suggests, actually generate their own light while using very little battery power, they have long been viewed as an obviously better way to create displays. While conventional L.E.D.'s work well in giant screens and advertising displays, they cannot easily be used to create small, high-resolution screens for portable computers. But displays made by OLEDs made from plastics and other organic (carbon-based) molecules rather than gallium nitride, promise to be not only more efficient but also easier on the eyes.

Organic LED display and liquid crystal display

The most sophisticated O.L.E.D. operate much like the color L.C.D. displays found on current laptops. On the back are thousands of transistors to control the thousands of pixels that are switched on or off to create images.

The similarities, however, end there. With a conventional L.C.D. screen, each pixel is divided into three subpixels, each filtered to display red, green or blue light. The L.C.D. units act as window blinds, appearing or disappearing in whatever combination an

image demands. For example, the screen appears to be entirely white when every L.C.D. opens and reveals all the subpixels (to the eye, the three primary colors blend to make white light). For a black screen, all the L.C.D.'s are closed to hide the screen's lamp, which nevertheless continues to glow and consume battery power.

OLED displays replace the lamp, the subpixels and the color filters with rows and rows of red, green and blue O.L.E.D. units. Unlike current screens, these new displays glow — and drain their batteries — only when needed. A completely black screen, for example, would draw no power. Because the light does not have to squeeze through a layer of color filters and a layer of L.C.D. shutters, the new displays do not look dim when viewed from an angle. And finally, by eliminating complex filtering and shuttering layers, it should be possible to make a screen of any resolution.

Unlike traditional LCD's, OLED's self-luminous and do not require backlighting, diffusers, polarizers, or any of the other baggage that goes with liquid crystal displays. Essentially, the OLED consists of two charged electrodes sandwiched on top of some organic light emitting material. This eliminates the need for bulky and environmentally undesirable mercury lamps and yields a thinner, more versatile and more compact display. Their low power consumption provides for maximum efficiency and helps minimize heat and electric interference in electronic devices. Armed with this combination of features, OLED displays communicate more information in a more engaging way while adding less weight and taking up less space

Organic LED display and liquid crystal display comparison

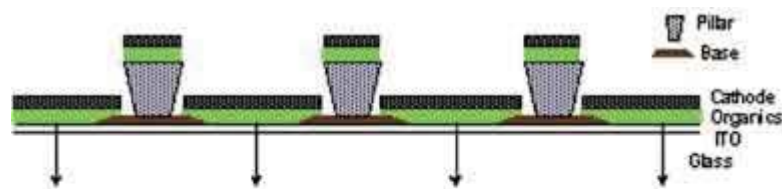
	An Organic LED panel	TFT liquid crystal panel
A luminous form	Self-emissions of light	Back light or outside light is necessary
Consumption electric power	It is lowered to about 1mW though it is a little higher than the reflection type liquid crystal panel. 10mW (100cd/m ²)	It is abundant when back light is used. 144mW (6cd/m ²)
Color indication form	The fluorescent material of RGB is arranged in order, and or a color filter is used	A color filter is used
High brightness	100cd/m ²	6cd/m ²
The dimension of the panel	It is produced to several - inches type, in the future, to about 10 - inch type. Goal	It is produced to 28 - inch type in the future to 30 - inch type. Goal
Contrast	100:1	6:1
The thickness of the panel	It is thin with a little over 1mm	When backlight is used it is thick with 5mm
The mass of the panel	It becomes lightweight more than 1g more than the liquid crystal panel in the case of the one for portable telephone	With the one for the portable telephone. 10g weak degree
Answer time	Several μ s	Several ms
A wide use of temperature range	86°C ~ -40°C	~ -10°C
The corner of the view	Horizontal 180°	Horizontal 120° ~170

There are two forms of OLED displays: Passive-matrix and Active-matrix.

Passive Matrix

The passive-matrix OLED display has a simple structure and is well suited for low-cost and low-information content applications such as alphanumeric displays. It is formed by providing an array of OLED pixels connected by intersecting anode and cathode conductors.

Organic materials and cathode metal are deposited into a “rib” structure (base and pillar), in which the rib structure automatically produces an OLED display panel with the desired electrical isolation for the cathode lines. A major advantage of this method is that all patterning steps are conventional, so the entire panel fabrication process can easily be adapted to large-area, high-throughput manufacturing.



Advantages:

- » Photolithography prior to organic/cathode depositions
- » High resolution possible
- » Scaleable to large areas

Typical patterning method for passive matrix OLED displays.

To get a passive-matrix OLED to work, electrical current is passed through selected pixels by applying a voltage to the corresponding rows and columns from drivers attached to each row and column. The more current pumped through each pixel diode, the brighter the pixel looks to our eyes. An external controller circuit provides the necessary

input power, video data signal and multiplex switches. Data signal is generally supplied to the column lines and synchronized to the scanning of the row lines. When a particular row is selected, the column and row data lines determine which pixels are lit. A video output is thus displayed on the panel by scanning through all the rows successively in a frame time, which is typically 1/60 of a second.

Active Matrix

In an active matrix display, the array is still divided into a series of row and column lines, with each pixel formed at the intersection of a row and column line. However, each pixel now consists of an organic light emitting diode (OLED) in series with a thin film transistor (TFT). The TFT is a switch that can control the amount of current flowing through the OLED.

In an active matrix OLED display (AMOLED), information is sent to the transistor in each pixel, telling it how bright the pixel should shine. The TFT then stores this information and continuously controls the current flowing through the OLED. In this way the OLED is operating all the time, avoiding the need for the very high currents necessary in a passive matrix display.

In contrast to the passive-matrix OLED display, active-matrix OLED has an integrated electronic back plane as its substrate and lends itself to high-resolution, high-information content applications including videos and graphics. In an active-matrix OLED display, each individual pixel can be addressed independently via the associated TFT's and capacitors in the electronic back plane. That is, each pixel element can be selected to stay "on" during the entire frame time, or duration of the video. Since OLED is an emissive device, the display aperture factor is not critical, unlike LCD displays where light must pass through aperture.

Therefore, there are no intrinsic limitations to the pixel count, resolution, or size of an active-matrix OLED display, leaving the possibilities for commercial use open to our imaginations. Also, because of the TFT's in the active-matrix design, a defective pixel produces only a dark effect, which is considered to be much less objectionable than a bright point defect, like found in LCD's

Active matrix OLEDs highlight a fundamental difference between organic LEDs and inorganic LEDs: No one has ever succeeded in integrating a similarly dense array of inorganic LEDs. Even less dense arrays tend to suffer from optical cross-coupling or mechanical complexity. For example, the LED television screens on large buildings are made up of hundreds of thousands of discrete devices.

Advantages

Robust Design - OLED's are tough enough to use in portable devices such as cellular phones, digital video cameras, DVD players, car audio equipment and PDA's.

Viewing Angles – Can be viewed up to 160 degrees, OLED screens provide a clear and distinct image, even in bright light.

High Resolution – High information applications including videos and graphics, active-matrix OLED provides the solution. Each pixel can be turned on or off independently to create multiple colors in a fluid and smooth edged display.

“Electronic Paper” – OLED's are paper-thin. Due to the exclusion of certain hardware goods that normal LCD's require, OLED's are as thin as a dime.

Production Advantages – Up to 20% to 50% cheaper than LCD processes. Plastics will make the OLED tougher and more rugged. The future quite possibly could consist of these OLED's being produced like newspapers, rather than computer “chips”.

Video Capabilities – They hold the ability to handle streamlined video, which could revolutionize the PDA and cellular phone market.

Hardware Content – Lighter and faster than LCD's. Can be produced out of plastic and is bendable. Also, OLED's do not need lamps, polarizers, or diffusers.

Power Usage – Takes less power to run (2 to 10 volts).

Disadvantages

Engineering Hurdles – OLED's are still in the development phases of production. Although they have been introduced commercially for alphanumeric devices like cellular phones and car audio equipment, production still faces many obstacles before production.

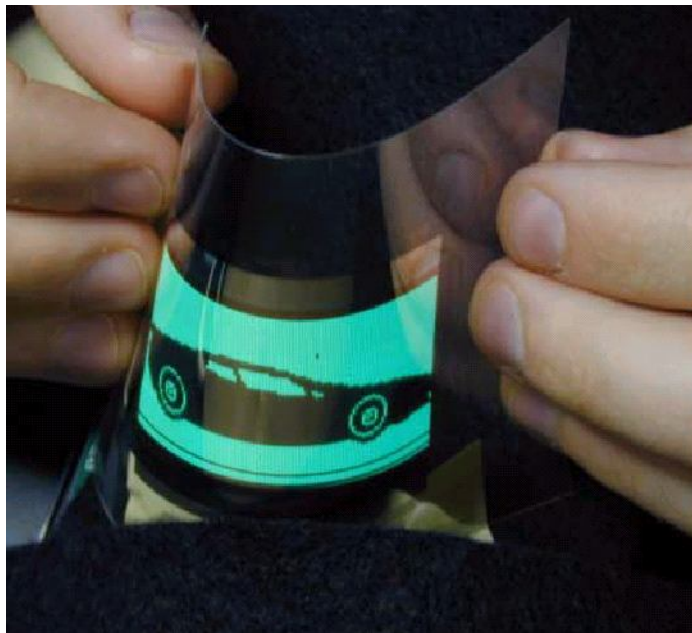
Color – The reliability of the OLED is still not up to par. After a month of use, the screen becomes nonuniform. Reds, and blues die first, leaving a very green display. 100,000 hours for red, 30,000 for green and 1,000 for blue. Good enough for cell phones, but not laptop or desktop displays.

Overcoming LCD's – LCD's have predominately been the preferred form of display for the last few decades. Tapping into the multi-billion dollar industry will require a great product and continually innovative research and development. Furthermore, LCD manufacturers will not likely fold up and roll over to OLED's. They will also continue to improve displays and search for new ways to reduce production costs.

Many advancements have been made in the OLED display field which further provides the OLED technology a bright future in the display market. Some of the developments are TOLED, SOLED, FOLED.

FOLED

FOLEDs or flexible OLEDs are organic light emitting devices built on flexible substrates. Flat panel displays have traditionally been fabricated on glass substrates because of structural and/or processing constraints. Flexible materials have significant performance advantages over traditional glass substrates.



Advantages

Flexibility: For the first time, FOLEDs may be made on a wide variety of substrates that range from optically-clear plastic films to reflective metal foils. These materials provide the ability to conform, bend or roll a display into any shape. This means that a FOLED display may be laminated onto a helmet face shield, a military uniform shirtsleeve, an aircraft cockpit instrument panel or an automotive windshield.

Ultra-lightweight, thin form: The use of thin plastic substrates will also significantly reduce the weight of flat panel displays in cell phones, portable computers and,

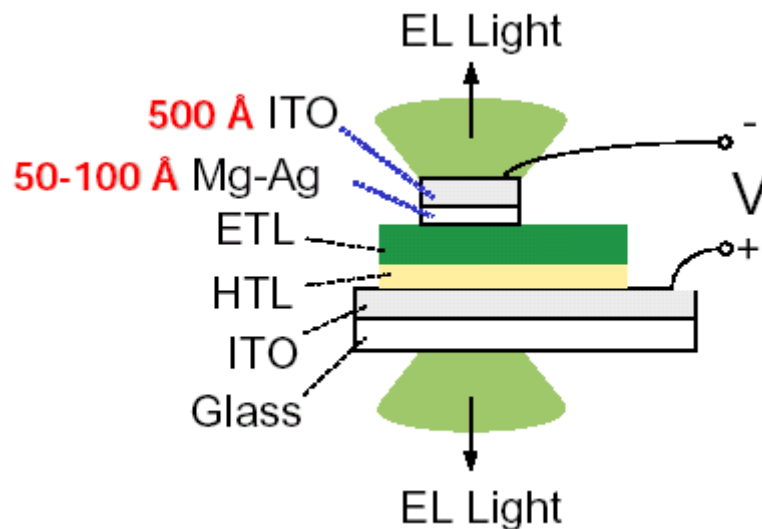
especially, large-area televisions-on-the-wall. For example, the weight of a display in a laptop may be significantly reduced by using FOLED technology.

Durability: FOLEDs will also generally be less breakable, more impact resistant and more durable compared to their glass-based counterpart.

Cost-effective processing: OLEDs are projected to have full-production level cost advantage over most flat panel displays. With the advent of FOLED technology, the prospect of roll-to-roll processing is created. While continuous web FOLED processing requires further development, this process may provide the basis for very low-cost, mass production.

TOLED

The Transparent OLED (TOLED) uses a proprietary transparent contact to create displays that can be made to be top-only emitting, bottom-only emitting, or both top and bottom emitting (transparent). TOLEDs can greatly improve contrast, making it much easier to view displays in bright sunlight.



Because TOLEDs are 70% transparent when turned off, they may be integrated into car windshields, architectural windows, and eyewear.

Their transparency enables TOLEDs to be used with metal, foils, silicon wafers and other opaque substrates for top-emitting devices.

Advantages

Directed top emission: Because TOLEDs have a transparent structure, they may be built on opaque surfaces to effect top emission. Simple TOLED displays have the potential to be directly integrated with future dynamic credit cards. TOLED displays may also be built on metal, e.g., automotive components. Top emitting TOLEDs also provide an excellent way to achieve better fill factor and characteristics in high resolution, high-information-content displays using active matrix silicon backplanes.

Transparency: TOLED displays can be nearly as clear as the glass or substrate they're built on. This feature paves the way for TOLEDs to be built into applications that rely on maintaining vision area. Today, "smart" windows are penetrating the multi-billion dollar flat glass architectural and automotive marketplaces. Before long, TOLEDs may be fabricated on windows for home entertainment and teleconferencing purposes; on windshields and cockpits for navigation and warning systems; and into helmet-mounted or "head-up" systems for virtual reality applications.

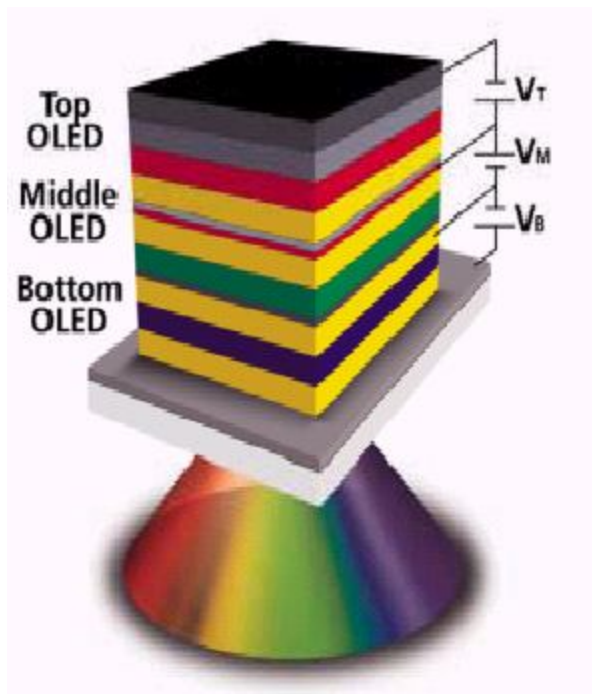
Enhanced high-ambient contrast: TOLED technology offers enhanced contrast ratio. By using a low-reflectance absorber (a black backing) behind either top or bottom TOLED surface, contrast ratio can be significantly improved over that in most reflective LCDs and OLEDs. This feature is particularly important in daylight readable applications, such as on cell phones and in military fighter aircraft cockpits.

Multi-stacked devices: TOLEDs are a fundamental building block for many multi-structure (i.e. SOLEDS) and hybrid devices. Bi-directional TOLEDs can provide two independent displays emitting from opposite faces of the display. With portable products

shrinking and desired information content expanding, TOLEDs make it possible to get twice the display area for the same display size.

SOLED

The Stacked OLED (SOLED) uses novel pixel architecture that is based on stacking the red, green, and blue subpixels on top of one another instead of next to one another as is commonly done in CRTs and LCDs. This improves display resolution up to three-fold and enhances full-color quality. SOLEDs may provide the high resolution needed for wireless worldwide-web applications.



A SOLED display consists of an array of vertically-stacked TOLED sub-pixels. To separately tune color and brightness, each of the red, green and blue (R-G-B) sub-pixel elements is individually controlled. By adjusting the ratio of currents in the three elements, color is tuned. By varying the total current through the stack, brightness is

varied. By modulating the pulse width, gray scale is achieved. With this SOLED architecture, each pixel can, in principle, provide full color. Universal Display Corporation's SOLED technology may be the first demonstration of a vertically-integrated structure where intensity, color and gray scale can be independently tuned to achieve high-resolution full-color.

The SOLED architecture is a significant departure from the traditional side-by-side (SxS) approach used in CRTs and LCDs today. Compared to SxS configurations, SOLEDs offer compelling performance enhancements:

Advantages

Full-color tunability: SOLEDs offer dynamic full-color tunability for "true" color quality at each pixel -- valuable when color fidelity is important.

High resolution: SOLEDs also offer 3X higher resolution than the comparable SxS display. While it takes three SxS pixels (an R, G and B) to generate full-color, it takes only one SOLED pixel -- or one-third the area -- to achieve the same. This is especially advantageous when maximizing pixel density is important.

Nearly 100% fill factor: SOLEDs also maximize fill factor. For example, when a full-color display calls for green, the red and blue pixels are turned off in the SxS structure. By comparison, all the pixels turn on green in a SOLED under the same conditions. This means that SOLED color definition and picture quality are superior.

Scalable to large pixel size: In large screen displays, individual pixels are frequently large enough to be seen by the eye at short range. With the SxS format, the eye may perceive the individual red, green and blue instead of the intended color mixture. With a SOLED, each pixel emits the desired color and, thus, is perceived correctly no matter what size it is and from where it is viewed.

Microdisplays based upon organic light-emitting diodes

The need for high information content and small size is the driving force behind the development of high-resolution microdisplays, by which we mean displays that are viewed close to the eye, with the aid of lenses. As with flat-panel displays, microdisplays provide access to large amounts of information, but with another level of portability and convenience. As with flat-panel displays, they also have the potential of enabling huge new markets that do not require the displacement of an entrenched existing technology. The opportunities for microdisplays with the new technology approach using organic light-emitting diode (OLED) emitters integrated onto silicon chips, in the context of portable or even wearable display systems is gaining speed.

A primary enabler of this new generation of displays is CMOS silicon technology, which permits an extraordinary amount of electronic complexity to be packaged on a small chip of silicon. With the proper display design, this complexity can be used to control the elements of an image display, forming what is known as an active matrix display. A new microdisplay technology, organic light emitting diodes (OLEDs), has emerged as nearly ideal transducers for use with silicon active matrix chips. The OLEDs are easily formed from evaporated thin films laid down on top of the silicon, the required voltages are low enough to allow the use of low cost silicon processes and the optical characteristics are well-suited for use with magnifiers. They are efficient, resulting in low power consumption, and the fact that they emit light rather than modulate transmitted or reflected light results in viewing modules that are smaller and lighter. The integration of OLEDs with integrated circuits permits many computer and video electronic system functions to be built directly on the silicon IC under the OLED layer, resulting in an ultra-compact system with lower overall system costs relative to alternate near-eye display technologies.

In an OLED microdisplay, a stack of thin solid organic films (totaling less than 1 micrometer) is applied to the electrodes on the surface of the silicon. In this case, the small electric current through each electrode causes the organic structure to emit light in an amount depending upon the voltage. The active matrix array is provided on the silicon IC underneath, along with considerable other circuitry to minimize the requirements for other ICs. Since the light is constantly emitted in almost all directions, there are no significant variations with angle or time, and consequently, relatively no significant variations with vibration small movements of the eye. Color is achieved by having a full-color spectrum white emitter and overlaid color filters which provide subpixels of red, green and blue, similar to that of a color TV tube or LCD notebook display. The overall result is a more life-like image even when highly magnified to create a large field of view. The handling of color information in parallel, rather than sequentially, results in a lower power consumption and eliminates the need for an illumination source that simplifies and lightens the optics requirement for the display. A single low cost optical element can provide a large field of view virtual image. Since the light emitting sources only use power where light is needed, they more effectively use light than would be used in a full area illumination source for a liquid crystal on silicon display.

In AM displays, there is at least one driver transistor at each pixel (two for OLEDs). The same strobing as just described is carried out, but what it does is to cause a transistor to turn on and conduct, storing a charge on a capacitor. This capacitor in turn is connected to the gate of a second transistor, and causes the latter to conduct charge to the OLED pixel, a process that continues until another signal is applied to discharge the capacitor. Thus the OLED emits continuously. The disadvantage is that while 1120 driving transistors were needed for a PM VGA display, 614,400 additional ones are needed for AM, and they must be placed at each pixel, rather than in groups at the edge. (For color, separate drivers are needed for each color subpixel).

The best match to the range of microdisplay requirements is achieved by the combination of OLEDs on silicon. OLEDs are efficient Lambertian emitters that operate

at voltage levels (3–10 V) accessible with relatively low-cost silicon. They are capable of extremely high luminance (>100000 cd/m²), a characteristic which is especially important for military pilot helmet applications, even though most of the time they would be operated at much lower levels. Luminance is directly linear with current, so gray scale is easily controlled by a current-control pixel circuit. OLEDs are very fast, with response speeds superior to those of liquid crystals, an important feature for video displays. Fabrication is relatively straightforward, consisting of vacuum evaporation of thin organic layers, followed by thin metal layers and a transparent indium–tin oxide layer. A whole wafer can be processed at one time, including a process for sealing, before the wafer is sawed into individual displays. Up to 400 small displays (QVGA format using a 12- μ m color pixel pitch and a die size of 8 mm \times 7 mm) can be produced from a single 8-in. wafer, including interface and driver electronics embedded in the silicon.

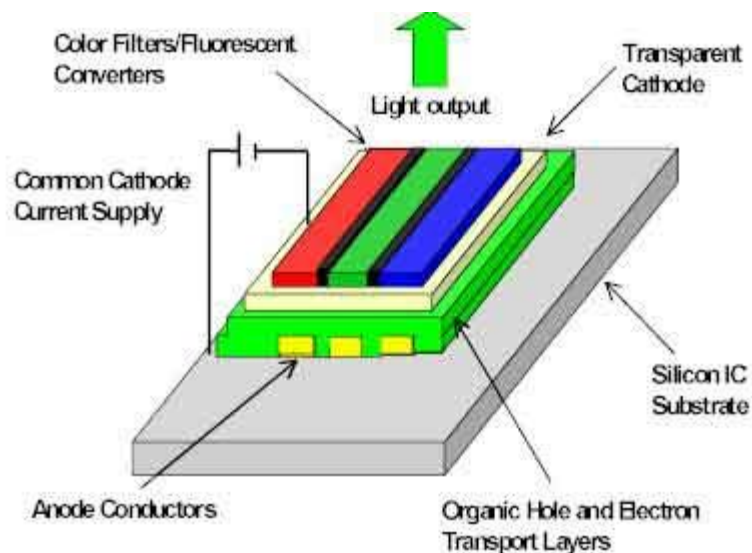


Diagram of a top-emitting OLED-on-silicon microdisplay

Even though an OLED microdisplay on silicon may have millions of subpixels, the OLED formation can be rather simple, because the complexity is all in the substrate. For each subpixel, corresponding to a red, green, or blue dot, there is a small electrode

pad, possibly $4\ \mu\text{m} \times 14\ \mu\text{m}$, attached to an underlying circuit that provides current. The OLED layers can be deposited across the whole active area, using shadow masking in the evaporator. This includes the cathode, which is common for all pixels. This simple approach is made possible by the fact that the materials are not good lateral conductors, so the very thin organic films cannot shunt current from one subpixel to another. With such thin structures, light also does not leak into adjacent pixels, so contrast is maintained even between neighboring pixels.

The use of silicon chip technology allows a number of functions to be integrated within the display including SRAM memory function at each pixel, simplifying system requirements.

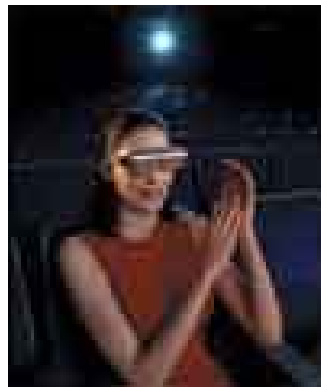
The temperature range of OLEDs greatly exceeds that of LCDs and exhibits very little color shift with temperature over even military specification environmental extremes. OLEDs are extremely thin compared to most other displays, making it possible to compact more pixels per unit area more easily than in most other flat-panel technologies. OLEDs are also one of the fastest switching, analog gray level controllable flat-panel displays in existence, making full-motion video at any refresh rate simple. In spite of the current impressive performance parameters being now shown, considerable room for future improvement in almost all parameters also appears to still be possible from this relatively new display technology.

OLED devices are very sensitive to moisture, which attacks the cathode materials; to a lesser degree, they are sensitive to oxygen, which can potentially degrade the organics. For this reason they must be sealed in an inert atmosphere after fabrication and before being exposed to ambient environmental conditions. OLEDs on silicon can be sealed by soldering a metal flange with a glass window directly to the surface of the silicon wafer (which is covered with insulating silicon dioxide).

OLED Microdisplay Applications

Since the combination of a microdisplay and optics can produce a virtual image, it can appear to be a large screen at a great distance (for example, a 10-ft diagonal screen ten feet away) or a conventional monitor at desktop working distance (for example, a 19-in. diagonal screen at 20-in. distance). The image can be superimposed on the external world in a see-through optics configuration, or, with independent displays for both eyes, a true 3D image can be created.

There are a host of potential applications, starting with entertainment headsets potentially the highest-volume market. In this application, a two-display lightweight binocular headset provides the illusion of watching a movie on a cinema-sized screen. The user could be in the back seat of an automobile, on a train or airplane, lying in bed, or on a beach.



Another potentially large market is for use with wearable computers, ultralight portable systems for which a light, monocular microdisplay headset would provide the full capabilities of a CRT monitor or a liquid crystal flat panel. Thinking about the uses of a wearable computer, one imagines that all kinds of information could be available on an “anytime, anyplace” basis. Schedules, e-mail, documents, business reports, etc. could be reviewed anywhere, with complete privacy. While touring a warehouse or storage yard, one could, with a bar-code wand, bring up all of the relevant information about an

item. Maintenance and repair personnel could have service manuals, even service videos, available for hands-free reference. If wireless capability is added, the whole world of the Internet becomes accessible.



Another potentially large market for microdisplays is the 3G (third-generation) cellular phone, or cell phone, in which all of the systems will support wideband access to data and images, including Web pages. Since it has been forecast that most business-to-business transactions will take place over the Internet, a cell phone that provides Internet access will be as essential as a voice cell phone is today. This could be accomplished, as it is today, by reformatting Web pages for apportionment on small, low-resolution displays; however, it could be done by including in the cell phone a microdisplay viewer capable of showing the information unchanged.



Markets that are smaller but still important include helmet displays for pilots and soldiers, capable of providing cueing, infrared images, maps, etc., and head-mounted displays for medical practitioners, showing X-rays, patient status, endoscopic images, etc

Product Concepts

The OLED technology has the potential to not only improve existing products, but also to create exciting, new product possibilities, for example:

- Low-power, bright, colorful cell phones
- Full color, high-resolution, personal communicators
- Wrist-mounted, featherweight, rugged PDAs
- Wearable, form-fitting, electronic displays
- Full-color, high resolution, portable Internet devices and palm size computers
- High-contrast automotive instrument and windshield displays
- Heads-up instrumentation for aircraft and automobiles
- Automobile light systems without bulbs
- Flexible, lightweight, thin, durable, and highly efficient laptop screens
- Roll-up, electronic, daily-refreshable newspaper
- Ultra-lightweight, wall-size television monitor
- Office windows, walls and partitions that double as computer screens
- Color-changing lighting panels and light walls for home and office
- Low-cost organic lasers
- Computer-controlled, electronic shelf pricing for supermarkets and retail stores
- Smart goggles/helmets for scuba divers, motorcycle riders
- Medical test equipment
- Wide area, full-motion video camcorders
- Global positioning systems (GPS)
- Integrated computer displaying eyewear
- Rugged military portable communication devices