LIGHT-EMITTING POLYMERS: THE REVOLUTIONARY DISPLAY TECHNOLOGY

Cambridge Display Technology, the UK, is betting that its lightweight, ultra-thin, lighting emitting polymer (LEP) displays have the right stuff to finally replace the bulky, space-consuming, and power-hungry cathode ray tubes (CRTs) used in television screens and computer monitors and become the ubiquitous display medium of the 21st century

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Light-emitting polymers (LEPs) or polymer-based light-emitting diodes (LEDs) discovered by Friend et al in 1990 have been found to be superior than liquid crystal displays (LCDs), vacuum fluorescence displays, and electroluminescence displays. Though not commercialised yet, these have proved to be a milestone in the field of flat-panel displays (FPDs). Research on LEP is underway in Cambridge Display Technology Ltd (CDT), Cambridge, the UK.

The cathode ray tube (CRT), invented by German physicist Karl Ferdinand Braun in 1897, remained the ubiquitous display in the last half of the 20th century. But the CRT's long heritage in an environment where product life cycles are measured in months rather than years doesn't mean that it is the ideal display solution. It is bulky, power hungry, and expensive to manufacture.

The fact is that researchers have not come up with a better solution. Liquid crystal display (LCD) was pitched as the saviour of the display industry. Its creators claimed that a slim profile would quickly make it the display of choice. But today, LCDs are far from pervasive. These offer little benefit over their predecessor, the CRT. The cost of an LCD as well as a CRT monitor constitutes one-third of the total price of the computer.

Says David Mentley, vice president and display industry analyst at Stanford Resources, California, USA, "Although the LCD is a highly successful technical achievement, the manufacturing archetype must change if flat-panel displays are to compete directly across all applications."

In the last decade, several other contenders, such as plasma and field emission displays, were hailed as the solution to the pervasive display. Like LCD, they suited certain niche applications, but failed to meet the broad demands of the computer industry.

What if a new type of display could combine the characteristics of a CRT with the performance of an LCD and the added design benefits of formability and low power? Cambridge Display Technology Ltd (CDT) is developing a display medium with exactly these characteristics. The technology uses a light emitting polymer (LEP) that costs much less to manufacture and run than CRTs because the active material is plastic.


SEC/CDT full-colour LEP display

What is LEP

It is a polymer that emits light when a voltage is applied to it. The structure comprises a thin-film semiconducting polymer sandwiched between two electrodes (anode and cathode). When electrons and holes are injected from the electrodes, the recombination of these charge carriers takes place, which leads to emission of light that escapes through glass substrate. The bandgap, i.e. energy difference between valence band and conduction band, of the semiconducting polymer determines the wavelength (colour) of the emitted light.

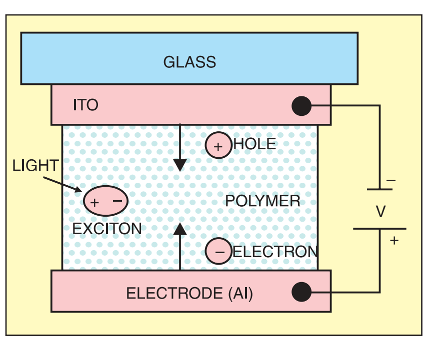

Fig. 1: The structure of a light-emitting polymer device

Chemistry behind LEP

Plastic materials have replaced traditional materials such as natural polymers (wood), metals, ceramics, and glasses in many applications, owing to their physical/mechanical properties (light weight combined with physical strength) and ease of processibility (the ability to mould the shape or extrude into sheet and rod through a die). For over the last 30 years, there has been an increasing interest in exploiting these characteristics of polymer materials in combination with electrical properties over and above the purely insulating characteristics.

The first polymer LEDs used poly or phenylene vinylene (PPV) as the emitting layer. Since 1990, a number of polymers have been shown to emit light under the application of an electric field; the property is called electroluminescence (EL). PPV and its derivatives, including polythiophenes, polypyridines, poly (pyridyl vinylene), polyphenylenes, and copolymers, are still the most commonly used materials. Efforts are on to improve stability, lifetime, and efficiency of polymer devices by modifying their configuration.

Plastic materials with metallic and semiconductor characteristics are called conjugated polymers. The overlap of Pz orbital in these polymers leads to the formation of a delocalised pi electron cloud above and below the plane of sigma bonds that form the structural framework. This delocalised pi-electron system along the polymer backbone confers semiconducting properties to the polymer and gives it the ability to support positive and negative charge carriers with high mobility along the polymer chain.

If the Pz orbital overlap is over several sites, well delocalised pi valence and pi* conduction bands with an energy gap between these are formed—the cause for semiconducting behaviour.

The charge transport mechanism in conjugated polymers is different from traditional inorganic semiconductors. The amorphous chain morphology results in inhomogeneous broadening of the energies of the chain segments and leads to hopping type transport. A secondary effect is the distortion of the chain around a charge carrier. This is why the charged excitations are usually described as polarons in conjugated polymers.

Basic working

Like the CRT, LEP emits light as a function of its electrical operation. An LEP display solely consists of the polymer material manufactured on a substrate of glass or plastic and doesn't require additional elements like the backlights, filters, and polarisers that are typical of LCDs.

Fig. 1 shows the structure of an LEP device. The indium-tin oxide (ITO) coated glass is coated with a polymer. On the top of it, there is a metal electrode of Al, Li, Mg, or Ag. When a bias voltage is applied, holes and electrons move into the polymer. These moving holes and electrons combine together to form hole-electron pairs known as 'excitons'. These excitons are in excited state and go back to their initial state by emitting energy. When this energy drop occurs, light comes out from the device.

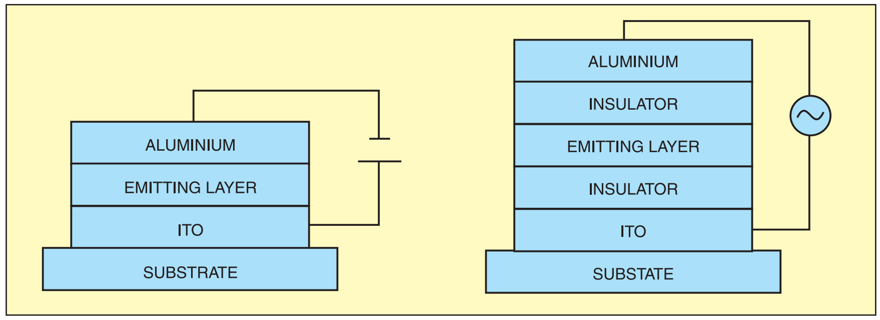

Fig. 2: The structure of (a) single-layer device and (b) symmetrically configured alternating current light emitting (SCALE) device

Light-emitting devices consist of active/emitting layers sandwiched between a cathode and an anode. Indium-tin oxide is typically used for the anode and aluminium or calcium for the cathode. Fig. 2(a) shows the structure of a simple single-layer device with electrodes and an active layer. Single-layer devices typically work only under a forward DC bias. Fig. 2(b) shows a symmetrically configured alternating current light-emitting (SCALE) device that works under AC as well as forward and reverse DC bias.

Manufacturing

Philips has pioneered the LEP technology and is working toward its commercialisation. The company is using the existing manufacturing technologies during production, keeping the special processes, especially the polymer treatment, to a bare minimum.

In order to manufacture the polymer, a spin-coating machine is used that has a plate spinning at the speed of a few thousand rotations per minute. The robot pours the plastic over the rotating plate, which, in turn, evenly spreads the polymer on the plate. This results in an extremely fine layer of the polymer having a thickness of 100 nanometres. Once the polymer is evenly spread, it is baked in an oven to evaporate any remnant liquid. The same technology is used to coat the CDs.

Types of LEPs

The types of organic light-emitting devices available in the market include flexible, stacked, and transparent.

Flexible organic LEDs (FOLEDs). FOLEDs are built on flexible substrates. Flat-panel displays have traditionally been fabricated on glass substrates, in part because these have intrinsic structural and/or processing constraints that preclude the use of non-rigid substrates. Nonetheless, flexible materials are highly desired substrates because these have significant performance and cost advantages.

A passive-matrix 0.18mm thick FOLED fabricated in UDC's pilot line facility

UDC's proprietary FOLED technology is the result of a pioneering work to demonstrate that OLEDs are functional and durable in a flexible format and can be built with the same performance as their rigid substrate counterparts.

Flexibility. For the first time, FOLEDs may be made on substrates ranging from optically clear plastic films to reflective metal foils. These materials provide the ability to conform, bend, or roll a display into any shape, so a FOLED may be laminated onto helmet face shields, military uniforms, shirtsleeves, aircraft cockpit instruments panel, or automotive windshields.

Ultra-lightweight, thin form. The use of thin plastic substrates will significantly reduce the weight of flat-panel displays in cell phones, portable computers, and especially large-screen on-the-wall-televisions. For instance, the display in a laptop can be reduced from several pounds to a few ounces by using FOLED technology.

Durability. FOLEDs are generally less fragile and more impact-resistant and durable than their glass-based counterparts.

TOLED and SOLED features. FOLEDs offer excellent performance characteristics and features of both TOLEDs and SOLEDs.

Cost-effective processing. Researchers have demonstrated a continuous organic vapour phase deposition method for large-area roll-to-roll FOLED processing. While this technique requires further development, it provides the basis for very low-cost mass production.

SOLEDs. The award-winning stacked OLED (SOLED) pixel architecture is a radical new approach for full-colour displays. UDC's proprietary SOLED technology offers high-definition display resolution and true-colour quality for next-generation display applications.

The SOLED consists of an array of vertically stacked TOLED sub-pixels. To separately tune colour 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, colour is tuned. By varying the total current through the stack, brightness is varied. By modulating the pulse width, grayscale is achieved. With this SOLED architecture, each pixel can provide full colour.

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

- Full-colour tunability for true colour quality at each pixel—valuable when colour fidelity is important.
- Three times higher resolution than the comparable SxS display. While it takes three SxS pixels (R, G, and B) to generate full colour, it takes only one SOLED pixel—or one-third the area—to achieve the same. This is especially advantageous when maximising pixel density is important.
- Nearly 100 per cent fill factor; for example, when a full-colour display calls for green, red and blue pixels are turned off in the SxS structure, whereas all the pixels turn on green in a SOLED under the same conditions. This means that SOLED colour definition and picture quality are superior.
- No upper limit to pixel size. In large-screen displays, individual pixels are frequently large enough to be seen by the eye at a short range. With the SxS format, the eye may perceive individual red, green, and blue instead of the intended colour mixture. With a SOLED, each pixel emits the desired colour and thus is perceived correctly, no matter what size it is and from where it is viewed.

TOLEDs. TOLEDs employ an innovative transparent contact to achieve an enhanced display. With this proprietary transparent OLED structure, TOLEDs can be top, bottom, or both top and bottom emitting (transparent). This option creates a host of exciting new display opportunities.

In its most basic form, the TOLED is a monolithic solidstate device consisting of a series of small-molecule organic thin films sandwiched between two transparent, conductive layers (refer to Fig. 3). As a result, TOLEDs are bright, self-emitting displays that can be directed to emit from either or both surfaces. This is possible because in addition to having transparent contacts, the organic materials are transparent over their own emission spectrum and throughout most of the visible spectrum.

Structure. A transparent conductive material such as indium-tin oxide for hole injection is deposited directly onto a glass substrate. Then a series of organic materials are deposited by vacuum sublimation on the indium-tin oxide layer: The first organic layer serves as a hole-transporting layer (HTL) and the second layer serves

Advantages of LEPs Over Other Displays

- Require only 3.3 volts and have lifetime of more than 30,000 hours.
- Greater power efficiency than all other flat-panel displays.
- No directional or blurring effects.
- Can be viewed at any angle.
- Display fast moving images with optimum clarity.
- Cost much less to manufacture and to run than CRTs because the active material is plastic.
- Can scale from tiny devices millimetres in dimension to high-definition devices up to 5.1 metres in diameter.
- Fast switching speeds that are typical of LEDs.
- Higher luminescence efficiency. Due to a high refractive index of the polymer, only a small fraction of the light generated in the polymer layer escapes the film.

Stacked organic light-emitting device

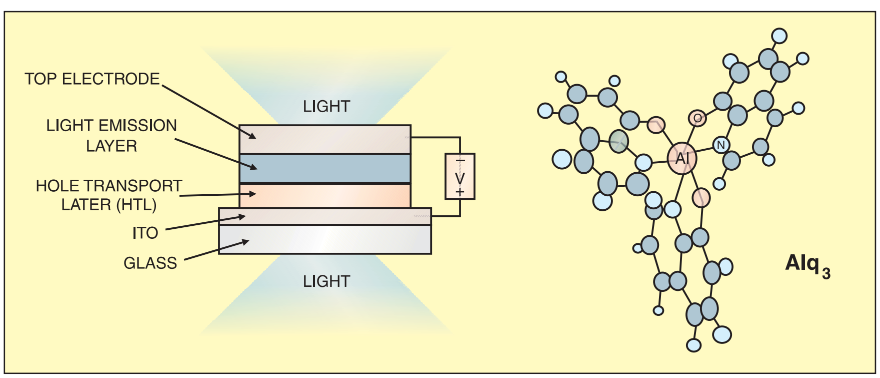

Fig. 3: TOLED structure

as both a light emitting layer (EL) and an electron-transporting layer (ETL). Finally, a UDC proprietary transparent contact for electron injection is deposited by vacuum evaporation or sputtering on the top of the organic films.

When a voltage is applied across the device, it emits light. This light emission is based upon the luminescence phenomenon, wherein injected electrons and holes migrate from the contacts toward the organic heterojunction under the applied electric field. These carriers meet to form excitons (electron-hole pairs) that recombine radiatively to emit light.

Compared to other FPDs, TOLEDs offer better energy efficiency (hence longer battery life), full viewing angle, brighter and higher-contrast light emission, faster response, and better environmental robustness. These thin-film, solidstate devices are durable and ideal for portable applications. In full production, TOLEDs cost significantly less than LCDs because these require fewer process steps and use fewer and lower-cost materials than LCDs.

Directed top emission. As standard OLEDs have reflective back contacts, these are bottom emitters and must be built on transparent substrates. TOLEDs have a transparent structure, so these may instead be built on opaque surfaces to effect top emission. These displays have the potential to be directly integrated with future dynamic credit cards and may also be built on metal, e.g. automotive components.

Top-emitting TOLEDs achieve better fill factor and characteristics in high-resolution, high-information-content displays using active-matrix silicon back-planes.

Transparency. TOLEDs can be as clear as the glass or the substrate they're built on. TOLEDs built between glass plates are transparent up to 70 per cent or more when turned off. This indicates the potential of TOLEDs in applications where maintaining vision area is important.

Today, smart windows are penetrating the multibillion dollar flat-glass architectural and automotive marketplaces. 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. TOLEDs offer enhanced contrast ratio. By using a low-reflectance absorber (a black surface) behind the top or the bottom TOLED surface, contrast ratio can be significantly improved. This feature is particularly important in daylight readable applications; for examples cell phones and military fighter aircrafts' cockpits.

Multi-stacked devices. TOLEDs are fundamental building blocks for many multistructure and hybrid devices; for example, UDC's novel, vertically-stacked SOLED architecture. Biplanar TOLEDs will give two readouts through one surface. Bidirectional TOLEDs will provide two independent displays emitting from opposite faces of the display. With portable products shrinking and desired information content expanding, TOLEDs are a great way to double the display area for the same display size!

Aging of LEP

One of the major barriers to the commercial development of light emitting devices based upon electroluminiscent polymers is their useful lifetime. The lifetime of these devices can be greatly extended by operating in an inert environment under dry box conditions. However, even under ideal conditions, the light intensity gradually decreases and some discrete regions become totally dark.

Various tests like AC impedance measurement and optical microscopy are being carried out in Cambridge University to determine physical and/or chemical changes that correlate with the loss of electroluminiscent intensity from polymeric light emitting devices and thereby find out the way to increase the useful lifetime. One problem that the engineers encountered was to stop or delay the aging process of the polymer. The trickiest stage was the final soldering of the displays—this needed to be done in an airtight environment because as soon as the LEP molecules came in contact with oxygen, these would disintegrate. The solution was to do the soldering in a glass jar filled with nitrogen. The enclosure protects the device from impurities and provides a higher degree of efficiency by giving the screen an estimated life span of 30,000 working hours.

Space charge effect

The effects of space charge on the current-voltage (I-V) and capacitance-voltage (C-V) characteristics of polymer LEDs have been investigated theoretically. Space charge effects are important in polymer LEDs due to the low carrier mobilities and significant recombination in the device. This effect becomes more pronounced as the difference between electron and hole mobilities is increased.

Multi-/full-colour cellular phone display

Consequences of space charge include lowering of the electric fields near the contacts and therefore suppression of the injected tunnelling currents, and strongly asymmetric recombination profiles for unequal mobilities thereby decreasing the luminescence. Research is underway to overcome this barrier.

Potential applications

The wall of a home may serve as a direct connection to the outside world. One can interact and follow all the latest breaking news, sports, and weather in the comfort of one's home with flat-display technology. The clarity of the images obtained with OLED technology may make realistic interaction with distant locations possible.

About ten years from now, we'll find LEP in every sphere of life. The various possible applications of LEPs include multi-/full-colour cell phone displays, full-colour high-resolution personal digital assistants (PDAs), heads-up instrumentation for cars, lightweight wristwatches that double as high-definition TVs, roll-up daily-refreshable electronic newspapers, automobile light systems without bulbs, office windows/walls/partitions that double as computer screens, etc.

Conclusion

LEPs are promising, low-cost solutions for today's flat-panel displays. Although not commercialised yet, these may replace bulky and heavy CRT displays in the near future. At the *Wall Street Journal CEO Forum* that took place in London, the UK, a panel of industry leaders predicted that LEP technology would storm the market in the next few years. ❑

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