THIN FILM ENCAPSULATION OF OLED DISPLAYS
- A MAJOR TECHNOLOGY CHALLENGE -

OLED displays are in many ways superior to LCD displays in screen experience, lower weight and adaptability to innovative product designs. However, as with any new technology, OLED has some significant technical challenges to solve. Examples of such challenges are blue pixel lifetime, inefficient use of very expensive OLED materials and encapsulation.

In particular, encapsulation, perfectly sealing the OLED away from moisture and oxygen, remains a very significant challenge.

Encapsulation of OLED screens is currently most often accomplished by sandwiching display material between two plates of glass and sealing the edge. This method is expensive, especially for large screens. Further, double glass is fragile and inflexible and limits the potential of OLED for innovative and flexible display products.

Accomplishing encapsulation by very thin, transparent, impermeable films would provide many advantages. The advantages include it being unbreakable, having lower weight and thickness than glass, and being flexible. Thin film encapsulation is approaching mass production with a proprietary encapsulation process, the Vitex process. However, this process can only be used by one company, is quite expensive and is unsuitable for large displays. Thus for large displays, and for the other display makers, there remains a substantial need for a thin film and flexible encapsulation technology that lowers cost and helps revolutionize the display industry.

OLED – Superior to LCD, but harder to manufacture

Active matrix OLED is the fastest growing next generation display technology and in the next 5-10 years is destined to dominate the display market. It is superior to LCD in many ways: it has better color images (100% color gamut), and faster refresh (at least 10x), is much thinner, has much lighter (up to 100x) screens, and uses less electricity (up to 40% less than LED/LCD). Thin and light OLED screens will benefit large screen TV's. With the capability of also being flexible, OLED also enables a future of wearable devices and foldable screens.

Samsung 55" Curved OLED TV (DisplaySearch - Presentation at OLED World Summit 2013)

High development costs and limitations in manufacturing technology have thus far limited the widespread deployment of OLED displays.

First, OLED materials have finite lifetimes due to degradation of the emitting material with use. Red and green OLED materials have achieved lifetimes of 100,000 hours or more. But blue OLED material remains a

challenge. At a given brightness the lifetime is much shorter for blue pixels than green or red ones. Lifetimes of about 10,000 hours, or more, are now achievable for blue pixels operated under normal conditions. Architectures using multiple blue pixels driven at lower intensity and including pixels with longer lasting light blue OLED material helps to achieve the required lifetimes of at least 50,000 hours for large screen televisions and 20,000 to 30,000 for tablets and laptops.

OLED materials are typically quite expensive at $500/gram or more. When deposited using vapor phase disposition (VPD) and a shadow mask as much as 80% of the OLED material can end up on the mask or deposition head instead of on the device. To reduce the amount and cost of wasted material, direct printing methods such as ink-jet are actively being pursued. However, ink-jet printing cannot yet achieve the same high screen resolution as VPD with shadow masks. For smaller screens up to Gen 5 sized substrates, the thin metal shadow masks may still be manageable. But once manufacturing reaches large screens made from Gen 8 substrates, the direct print methods will be required for both cost and shadow mask handling limitations.

In addition to the issues surrounding lifetime and cost of OLED materials a fundamental difficulty for OLED display screens manufacturing is the requirement to have the OLED layer be totally isolated from contact with air and moisture. In order to achieve this, the entire display structure must be perfectly sealed or encapsulated.

The most common encapsulation method currently uses two panes of glass enclosing the entire active matrix OLED structure, including the TFT pixel driving layers and OLED layers, and then sealing the surrounding edge.

The complexities of the double glass process drive up the costs of manufacturing OLED displays and the yields are such that they cannot be competitive with LCD displays.

Despite improvements to double glass encapsulation, display manufacturers do not see it as the best long-term solution. Thin film encapsulation is generally recognized as having far greater potential to enable lighter, lower cost and more robust screens. And thin film encapsulation is needed to enable the development of OLED screens made on flexible substrates.

OLED Thin Film Encapsulation Technology

The current leading thin film encapsulation technology for OLED screens is the Vitex Barix™ process, first developed in the USA by a spin-off from Battelle Laboratories.

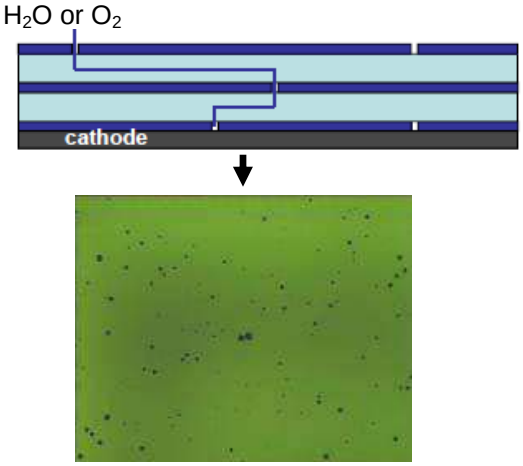

Figure 1, Vitex thin film barrier structure consists of multiple layers of dense barrier layers (dark blue) and soft organic layers (light blue).Moisture leaks appear as black spots that may grow over time.

As shown in Figure 1, the Vitex process provides a stack of alternating hard and soft layers totaling a few microns thick, much less than the thickness of a human hair yet expected to provide the moisture and oxygen penetration resistance of a vacuum chamber. This stack ensures a long meandering path for moisture and oxygen to reach and degrade the OLED materials even if barrier film defects are present. The long path approach has demonstrated a lifetime of 2 to 3 years for black spots to occur due to moisture or oxygen reacting with the OLED material. If these black dot defects can be avoided, thin film encapsulation is seen as a superior solution to glass. It is thinner, much lighter, unbreakable, and can even be used for curved screens on plastic.

In addition, highly flexible encapsulation could potentially enable tight-radius flexure in mobile devices. For example, a tablet-sized screen could be deployed from a pocket-sized mobile device.

Flexible OLED displays from Samsung (Presentation by DisplaySearch in 2012 OLED World Summit)

The difficulty with achieving these advantages is in finding a mass-production-worthy method for making moisture and air-impermeable thin films without defects. This challenge increases in proportion to the screen size and length of the expected lifetime for use. Thus, it is much more difficult to meet encapsulation requirements for TVs than for mobile devices due to their larger areas and longer expected lifetimes. It is beyond the capability of any current thin film barrier process, Vitex or other, to achieve less than several defects per square meter of screen size over a five to ten year life span. Furthermore, it is beyond current capability of any encapsulation technology to achieve such defect levels after being bent or flexed thousands of times in a tight radius of about a few centimeters or less.

In addition to the Vitex process, there are a number of different approaches for making thin film encapsulation barriers. The Panasonic or Philips processes use alternating pure inorganic layers of silicon oxide and silicon nitride. Composite films made of silicon oxide and silicon nitride layers tend to be stiff and can crack or become highly defective if bent or flexed. Another process that has been developed uses a single layer of mixed organic-inorganic material a micron thick or more. This mixed barrier layer is much thicker than purely inorganic barrier films. While this barrier is more flexible than purely inorganic barriers, it cannot, because of its thickness, be deposited at an economic rate by vapor phase methods. Some other experimental processes use plasma deposited layers alternating with painted-on liquid phase layers of mixed organic/inorganic content that are UV cured to make them much denser. Such barriers currently have high defect levels and will require further development before becoming a practical alternative.

Thin Film Barrier Requirements and Deposition Options

The key to the thin film encapsulation approach is the barrier layer(s) that actually stops the moisture and oxygen

from reaching the OLED material. To be effective as a barrier layer, the thin film needs first to have low reactivity with moisture or oxygen. In addition, it must also be dense and free of defects to prevent oxygen or moisture from migrating through the film. In order to not affect the image quality the barrier film must also be highly transparent. Finally, the above requirements must be met uniformly across large substrates with a deposition temperature of less than about 85°C to not damage the OLED materials.

There are three main alternative approaches to deposit dense barrier layers at low temperature: Physical Vapor Disposition (PVD), Plasma Enhanced Chemical Vapor Deposition (PECVD) and Atomic Layer Deposition (ALD).

PVD, also known as sputtering, is a traditional method to produce dense films at low-temperature. By PVD, aluminum oxide only about 25 nm thick effectively stops moisture and oxygen. However, PVD chambers are prone to produce particles that can cause film defects. In addition, the PVD films tend to have poor step coverage and be internally stressed. Thicknesses over about 50 nm are not practical with PVD due to deposition rate limitations and because they often crack if flexed.

PECVD has been the method of choice for depositing a multitude of layers in the well-established industry of manufacturing Integrated Circuits (IC's) and LCD panels. PECVD plasma sources are typically parallel plate systems with the substrate supported on a lower electrode facing an upper electrode which is typically a shower head gas injection plate. Most PECVD films are deposited at 250° C or higher to form fully reacted and dense films. This temperature is not suitable for OLED manufacturing since it will destroy the OLED emitter and other organic layers in the device. Lower temperature deposition processes have been developed by Philips and others but tend to have very low deposition rates resulting in low productivity for encapsulation equipment.

Finally, ALD uses alternating exposure to two separated reactive precursors to create two half-reactions that, when performed in sequence, will deposit thin films about an atomic layer at a time. Because of the sequential layering this technique has a low deposition rate and can be expensive to perform in mass production especially if films thicker than about 10 nm are required. Deposition temperature for ALD is generally above 100º C to fully complete the two half-reactions. To deposit low-temperature film additional energy needs to be added to the reactions using radicals and/or plasma treatments. Since the ALD barrier films are quite thin at 25 nm, and below they are physically fragile and must be protected by additional layers to remain intact. Finally, because ALD requires well matched half-reaction there is a limited number of films and compositions that can be grown by ALD limiting the choices achievable for films.

PlasmaSi Thin Film OLED Barrier

Of the methods available, the one most promising for thin film OLED barrier deposition is PECVD. It is a well-proven and cost-effective manufacturing method with the ability to grow a multitude of films with varied thickness and composition. However, for large substrates, standard PECVD approaches such as parallel plate reactors become very expensive and complex to operate.

Deposition rates become limited by reaction product removal and the shower head must be very complex to achieve uniform deposition results. And, once configured, a large parallel plate reactor has a limited process range within which to adjust film properties.

There are several requirementsPECVD-based thin film barrier deposition must meet:

- Deposition rate >100 nm/min at substrate temperature less than 80° C - to preserve the OLED material and allow for tolerance for variations in mass production.
- Film stress <±100 MPa and good adhesion to organic layers – required for compatibility with other materials making up the OLED display.
- Impervious to moisture and oxygen - meaning that the film should not incorporate certain atomic species or reaction by products that can enhance reactivity or permeability.
- Uniform thickness - less than ± 3% variation - across a several square meter substrate.
- Uniform film properties - such as refractive index, transparency and moisture resistance - across the entire substrate.
- Flexible films – bendable to small radius (less than 5 cm) hundreds or thousands of times.

PlasmaSi has developed a proprietary new plasma source technology to meet the above requirements. This source overcomes the limitations of parallel plate PECVD configurations and has the ability to tune film composition and characteristics as required for various applications.

With the PlasmaSi source it is possible to deposit 600nm of silicon nitride based barrier film directly on PEN plastic that has demonstrated life time in calcium testing of over 1100 hrs when exposed to an ambient temperature of 85º C/ 85% relative humidity. This result validates further evaluation and development of the PlasmaSi plasma source and barrier film as a solution to the challenges of manufacturing OLED displays with thin film encapsulation.

Summary and Conclusions

OLED displays will take increasing market share from LCD displays over the coming decade due to their innately superior image and their smaller screen thickness and weight. Switching from double glass encapsulation to thin film encapsulation will enable OLED displays to become less expensive and lighter and, in the future, flexible. Currently, many display manufacturers are evaluating alternative thin film processes for this application. While new technologies, such as ALD, may be seen as potential future solutions, they are fragile and costly to use in mass production. The proven technology of PECVD has the promise to become the method of choice to deposit thin film encapsulation barriers but needs substantial improvement to: provide uniform deposition on large substrates; avoid creating defects that allow moisture or oxygen to penetrate, and tailor film morphology that allows films to be flexible. PlasmaSi has developed a proprietary plasma source and nitride based barrier film that fulfills these requirements.