PSLA ADHESIVE MATERIAL OPTIONS FOR FLEXIBLE OLED PACKAGING

FROM LCD TO SSL—EDGE-LIT LIGHT GUIDES BRING PROVEN TECHNOLOGY TO GENERAL ILLUMINATION • A MODULAR APPROACH TO SSL PLANAR ILLUMINATING FIXTURES • DOES LED LIGHTING HAVE A TIPPING POINT?
Abstract:
Basic packaging schemes for organic light emitting diode (OLED) displays often incorporate an edge seal or pressure-sensitive/laminating adhesive (PSLA) to limit edge ingress of moisture vapor and oxygen. This article compares acrylic, siloxane and barrier rubber adhesive material options for use in flexible devices in terms of moisture permeability, adhesion and environmental stability. Our findings indicate that barrier rubber adhesive materials are often the best option due to their low moisture permeability, high optical quality and non-yellowing characteristics.

Overview of packaging schemes for OLED devices
The performance of organic light emitting diode (OLED) displays is steadily improving, and examples of these new capabilities were featured at the recent 2012 Consumer Electronics Show. Initial applications have evolved from simple, passive matrix-driven alphanumeric display devices to active matrix camera displays and OLED televisions as large as 55 inches. While the key enabler of these advances has improved the active emitting and charge transport materials within the devices, the packaging which protects them from moisture and oxygen has seen significant advancements as well. Approaches to the semi-hermetic packaging required by OLED displays have evolved steadily from early rigid glass-to-can and glass-to-glass structures to flexible displays on foil or plastic backings. With this packaging evolution has emerged the need for changes and understanding of packaging and encapsulation adhesive options. Generally, when packaging an OLED device, either a perimeter/edge sealed or laminated approach can be utilized. Many application-specific variants and combinations of these two basic packaging approaches are known, including those which utilize fillers and desiccant materials, and specific details are available in the literature. Perimeter sealing can often best be utilized within rigid devices, which are compatible with the batch process requirements for dispensing and curing typical edge sealants. Thermally fired glass frits which produce hermetically edge-sealed rigid devices require analogous batch processing. Lamination packaging approaches are often used for flexible devices because roll-to-roll processing is desired for lowering production costs and in-line roll lamination of film adhesives is readily achieved, in principle. Flexible laminating adhesives also alleviate many of the technical challenges related to forming a robust, curable edge seal bond which can withstand rigorous flexing.

In either the rigid perimeter sealed or the flexible laminated package, the moisture-sensitive OLED layer is sandwiched between two impermeable substrates. For rigid devices, one or both of those substrates are often glass. Common examples of rigid perimeter sealed packages include glass-to-glass OLED or electrophoretic displays perimeter sealed with UV or thermally curable highly filled epoxies or fired glass frit. For flexible devices, high barrier materials such as thin glass, steel foil or inorganically coated barrier plastics may be used. Various laminated OLED packaging schemes using inorganically coated high barrier plastic substrates with liquid or solid laminating adhesives have been demonstrated.
Focusing on flexible displays, two fundamentally different packaging scenarios exist. In the first, no other discrete barrier layers exist within the device aside from the impermeable front and back substrates. The barrier performance of the epoxy edge seals used in rigid OLEDs can be considered a minimum criterion for a flexible laminating adhesive within such a device. The presence or absence of desiccant materials in a flexible device will certainly affect this comparison, but for a first order approximation, this will not be further considered here. The perimeter sealed and basic flexible laminated packages are illustrated in Figure 1a and Figure 1b respectively (possible desiccant packet/layers omitted for clarity). In this case, the PSLA is in direct contact with the OLED active material layer, making chemical compatibility with that layer a critical consideration. Excellent optical quality and stability are required for top emission OLED structures in order to allow for high quality viewing through the adhesive layer. Adhesion must be at least as strong as the other layers in the laminate stack. In scenario two, an inorganic barrier layer is deposited over the surface and edges of the active OLED layers prior to lamination of the front substrate with the PSLA. In this case, the laminating adhesive plays no role in inhibiting moisture ingress because the back barrier substrate, in conjunction with the inorganic barrier layer deposited onto the device prior to packaging, meets this need. The laminating adhesive is required for securing the protective front sheet onto the device while absorbing possible impact, but not to stop permeant ingress. Also unlike scenario one, the adhesive does not come in direct contact with the active OLED stack, and the requirements for chemical inertness are technically relaxed to some degree. High optical quality and stability is still a requirement. This second packaging scenario is diagrammed in Figure 1c.

It is important to note that the barrier requirements for edge sealants and PSLA materials which prevent edge ingress (i.e. Fig. 1a and 1b) are very different when compared to the barrier requirements for the top and bottom film substrates. This is due to the longer permeation path length and smaller exposure area for a perimeter sealant vs. a high barrier film/substrate. A benchmark for edge ingress barrier requirements can be taken as the classic glass-to-can perimeter sealed packaging approach which is expected to attain a basic lifetime target of 10,000 hours with <10% loss of brightness at a defined drive current. Typically a desiccant packet or layer is used within the device to eliminate any moisture that could potentially permeate into the device as an added assurance measure for reaching the product lifetime goal. Highly filled UV or thermally curable epoxy adhesives can be taken as a benchmark for such semi-hermetic packages. (See Figures 1a-c.)

**Adhesive material classes for use in flexible laminated OLED packages**

Any materials intended for use in laminated or edge sealed packaging must exhibit several key characteristics. From the above discussion, low moisture permeability is clearly important. Also, the adhesive must be chemically compatible with the other components in the device. For a perimeter sealant, the requirement is often for ultra-low outgassing of low molecular weight components. Any lamination adhesive/PSA (Pressure Sensitive Adhesive) that is in direct contact with active layers of the OLED must also demonstrate chemical inertness with those underlying layers. Adhesion and mechanical strength of the bond must meet minimum requirements, but these vary widely with each packaging approach. Perhaps more importantly is the stability/reliability of adhesion during use and accelerated conditioning such as 85 °C/85% relative humidity (RH). Adhesives intended for use on the front of a top emission device must be non-yellowing and exhibit high light transmission, optical clarity and low haze. These optical require-
ments essentially eliminate the possibility of using traditional inorganic fillers or desiccants in PSLA adhesives through which viewing will occur.

The key basic physical requirements for OLED packaging adhesives in the three general packaging configurations discussed here are summarized in Table 1. These categories will be used hereafter to assess several PSLA adhesive classes. (See Table 1.)

The focus here will now be on pressure-sensitive and laminating adhesives (PSLA) for use in the bonding of barrier films or front sheets to flexible OLED displays or general lighting as shown schematically in Figure 1. Basic comparisons will be made across three representative classes of PSA materials: acrylics, siloxanes and barrier rubbers. These material classes are represented by the Adhesive Research’s 25 micron transfer film products EL-8154, IS-8026 and EL-92734 respectively.

**Permeability vs. Material Class**

As described above, the PSA layer in the laminated structure with no inorganic barrier layer on the device (Figure 1b) is required to exhibit good barrier properties which should be similar to those of a perimeter sealant given similar exposure areas and permeation path lengths. The exposure area is defined by the dimensions of the device and the bond line thickness (typically 25-50 microns). The path length is the width of the frame at the edge of device into which moisture can permeate before it affects the active layers, similar to the edge width of a perimeter sealant and approximately 1.2 mm. Data collected using a Moncon Permtran-W 3/33 analyzer for the classes of materials of interest is presented in Table 2. Analyses were conducted at 25 °C/100% RH with other specific conditions recorded as footnotes below the chart. Extensive tables of moisture and oxygen permeability data under various conditions are available in the literature, and the data below is generally consistent with those values. See Table 2

It is evident that for laminated packaging configurations such as that of Figure 1b, the only PSLA resin class which provides similar barrier properties to a filled epoxy is the barrier rubber EL-92734 PSA. This adhesive exhibits lower moisture permeability than a filled epoxy despite being unfilled in this testing. Because PSLA adhesives exhibit low Tg and modulus by design, they offer the benefit of being very flexible relative to a good epoxy perimeter sealant. For devices which incorporate an inorganic barrier layer inside the laminate construction as in Figure 1c, any of the acrylic, silicone or barrier rubber adhesives that could be considered as barrier properties are not critical. Although epoxy-based adhesive films can provide good barrier properties when properly designed, their use within large devices is typically limited by their shrinkage/stress buildup upon cure and tendency to yellow upon long-term exposure to oxygen and UVA (320-400 nm) radiation present in visible light (vide infra).

<table>
<thead>
<tr>
<th>Packaging Approach</th>
<th>Moisture/Oxygen Permeability</th>
<th>Adhesion</th>
<th>Optical Properties</th>
<th>Chemical Compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Perimeter Sealed</td>
<td>Good barrier properties needed</td>
<td>High adhesion and adhesion stability required</td>
<td>No requirements</td>
<td>No outgassing of small molecules or water</td>
</tr>
<tr>
<td></td>
<td>Fillers acceptable</td>
<td>Primary structural bond Flexible Laminated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible Laminated</td>
<td>Good barrier properties needed</td>
<td>Good adhesion required</td>
<td>Optical-grade adhesive layer required for top emission</td>
<td>High compatibility needed due to direct contact with OLED stack</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cannot be weak adhesive layer in device</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible Laminated with Inorganic Barrier Coating</td>
<td>No barrier requirements</td>
<td>Good adhesion required</td>
<td>Optical grade adhesive layer required for top emission</td>
<td>Inorganic barrier layer reduces chemical inertness requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cannot be weak adhesive layer in device</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of OLED Adhesive Key Attributes

Peel strength and stability vs. materials class

The adhesion peel force target can vary widely depending on specific application details, but is often not required to be extremely high. For example, in rigid or flexible laminated packages the adhesion of the PSLA to the OLED stack need only be higher than the adhesion of the organic or inorganic active layer to that substrate. Adhesion stability is often a more relevant property from both a physical bonding and chemical outgassing perspective. For OLEDs, which will be bent or flexed, the PSLA must not creep over time or the display’s edges will delam. In these instances, some level of chemical or physical cross-linking is typically employed to eliminate unwanted creep under ambient and appropriate elevated temperatures.

The PSLA classes studied here were compared by measuring peel force and peel stability after 85 °C/85% RH accelerated aging. The EL-8154 (acrylic), IS-8026 (silicone) and EL-92734 (barrier rubber) PSAs were used to form 1-inch wide laminations between 2 mil polyester film and glass and tested for 180° peel strength per ASTM D3330-83. Samples were allowed to dwell 24 hours under ambient conditions, and then tested initially and after 1-week and 2-weeks of aging at 85 °C/85% RH. The results of this test are summarized in Figure 2. The failure mode for all samples was primarily due to adhesive failure to the glass substrate.

The silicone pressure-sensitive adhesive (PSA) IS-8026 and the barrier rubber...
PSA EL-92734 exhibited excellent peel stability under all conditions. For IS-8026, this is expected given the hydrophobicity, high hydrolysis resistance and excellent thermal stability of siloxane-based materials. The EL-92734 barrier rubber is, similarly, a very hydrophobic, thermally and hydrolytically stable hydrocarbon material. As such, it exhibits peel stability similar to the silicone material. The EL-8154 acrylic also performed well, although it appears that peel values may have been beginning to decline more rapidly than the silicone and barrier rubber systems after aging at 85 °C/85 % RH for two weeks prior to testing. All samples exhibited peel forces which would be acceptable for most barrier sheet bonding and front sheet laminate applications, with the acrylic and barrier rubber materials performing slightly better in initial peel vs. the silicone in this respect. Overall, the excellent peel stability of the siloxane IS-8026 system makes it the most attractive selection for long-term outdoor use; particularly if moisture edge ingress is not critical for the specific application (i.e. an internal barrier layer is present as in Figure 1c). As previously noted, the much higher permeability of siloxanes vs. the barrier rubber system means stable barrier rubber adhesives such as EL-92734 will be favored when edge ingress into the device must be minimized through the PSLA. It should also be noted that the barrier rubber systems are significantly less expensive than silicone adhesives. See Figure 2.

**Optical clarity vs. material class**

The optical properties of the PSLA films
were evaluated using a BYK-Gardner Haze-Gard Plus. The percent transmission, haze and clarity for the adhesives are summarized in Table 3. A typical percent transmission target for a high end display is >98%. Typical display clarity and haze targets are >98% and <2% respectively as generic guidelines. The three classes of polymers that have been studied are all capable of being used in optical-grade laminations. It is notable that the optical quality achieved is also affected by the choice of liners and coating technique used for a given material, regardless of its inherent optical properties.

### UV stability comparisons

For top emission OLED displays and lighting, the light emitted from the active material is viewed through the PSLA adhesive. As such, the PSLA must exhibit good optical qualities and light stability. The PSLA classes studied were subjected to accelerated UV aging in a QUV Weatherometer. The EL-8154 acrylic, IS-8026 siloxane and EL-92734 barrier rubber PSA films were laminated to glass slides and exposed directly to QUV 340 nm bulbs. The UV-Vis spectra of the films were obtained initially and at periodic intervals over a 13-week aging period using a Perkin Elmer Lambda 900 Spectrometer equipped with a photodiode detector. None of the PSLA classes showed a significant increase in absorbance in the 400-800 nm range after accelerated UV aging for 13 weeks, which would be indicative of yellowing or chemical degradation. The highest absorbance value above 400 nm for the EL-8154, IS-8026 and EL-92734 were 0.053 AU, 0.055 AU, and 0.078 AU respectively. The maximum absorbance values for the PSLAs were similar to the baseline value for a glass slide substrate, and are attributed mainly to light scattering as opposed to absorbance. Representative UV-Vis data for the IS-8026 silicone PSA at time zero (red plot) and after 13 weeks (blue plot) of QUV exposure is shown in Figure 3. It is notable that EL-8154 utilizes an acrylic polymer which is designed for optical applications, and that many acrylics which contain heteroatom-functional monomers are less UV stable. The aromatic UV curable epoxies were tested and yellowed quickly when exposed to UV wavelengths, and are therefore not deemed optically stable enough to pass rigorous accelerated UV aging. The same is true of aliphatic epoxy systems, although discoloration occurs to a lesser degree in well-formulated systems. If UV filter/absorbing layers are incorporated in front of or in the PSLA layer, the inherent UV stability requirements for the polymer can be relaxed to some degree which is dependent on the absorption profiles of both the filter layer and the PSLA layer. Typical absorbing layers/films, which are still transparent enough through which to view the display, can help to extend the service life of an adhesive, but should not be relied on for complete UV protection. See Figure 3.

### Summary and Recommendations

For flexible OLED packaging which does not incorporate an inorganic barrier layer within the laminate structure, the PSLA selection quickly gravitates to barrier rubber adhesives due to their much lower moisture permeability vs. acrylics, siloxanes and even most epoxies. The high optical quality and UV stability which can be obtained from these systems make them the material class of choice in most cases. For packaging schemes which incorporate an inorganic barrier layer on top of the active OLED stack and underneath the PSLA and high barrier film, a broader range of adhesive classes can be considered because the barrier properties of the PSLA are, in principle, not crucial. Siloxanes are the highest performance choice in this scenario, but due to their high costs, barrier rubber systems become an attractive alternative along with well designed acrylic systems.

Specific packaging geometries and lifetime requirements will continue to evolve for roll-to-roll manufactured OLED displays and lighting, and so too will the exact composition of optimized edges seals and pressure-sensitive and laminating adhesives for those devices. As requirements for performance characteristics such as flexibility, specific adhesion, barrier prop-

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**Table 3. PSLA Optical Data**

<table>
<thead>
<tr>
<th></th>
<th>EL-8154</th>
<th>IS-8026</th>
<th>EL-92734</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acrylic</strong></td>
<td>100%</td>
<td>100%</td>
<td>99.2%</td>
</tr>
<tr>
<td><strong>Siloxane</strong></td>
<td>0.4%</td>
<td>0.6%</td>
<td>1.9%</td>
</tr>
<tr>
<td><strong>Barrier Rubber</strong></td>
<td>98.8%</td>
<td>99.0%</td>
<td>97.6%</td>
</tr>
</tbody>
</table>

**Figure 3. UV Stability of the IS-8026 Silicone PSA**
erties, chemical and light stability, and cohesive strength vary from one device structure to the next, a fundamental understanding of what can and cannot be achieved for various material class options is essential for adhesive selection. Given the variety of OLED applications under consideration and commercialization, the best PSLA choice will be dependent upon the specific needs of each application.

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References