Transparent Film Technology for Touch Screen and Flexible Display Applications

(Introduction)

Flexible electronic displays and touch screens are increasingly used in demanding outdoor environments. Design engineers are challenged to develop optical systems that meet a wide thermal range (-55°C to + 85°C) and comply with diverse optical, electrical and mechanical parameters. This paper discusses the optical and mechanical properties of substrates and thin and thick film coatings used in the production of flexible displays and touch screens. The paper also describes material limitations and opportunities to improve properties and functionality.

A great deal of interest surrounds flexible displays and touch screens. These technologies are used in a variety of commercial, industrial and military applications. Resistive and projective capacitive touch screens are widely used as convenient user interfaces in smart phones, point of sale devices and ruggedized display systems. Lighter weight, thinner profile and lower manufacturing costs make flexible displays with integrated touch screens attractive. An unbreakable display that provides good optical properties, requires low power and is cost-effective would certainly be in great demand. Flexible displays with touch screens are being investigated and developed for wrist-mounted displays, electronic books and paper, cell phones, and tablet computers. In addition, technology applicable to flexible displays and touch screens is already being used in the manufacture of photovoltaics, RFID tags, solid state lighting (OLEDs and LEDs), and most recently, transparent displays.

Market research cited in a 2010 Display Bank report estimates the market for flexible displays will exceed $5.0 billion in 2015 and $12.0 billion by 2018. This type of prodigious growth makes the market for materials used in flexible displays and touch screens very attractive.

However, material suppliers and display and touch screen design engineers face significant technical challenges in the development and manufacturing of flexible, optical materials including:

- Display and touch screen format – The flexural modulus must be defined for use in product fabrication and functionality. In order to have a complete user interface system, both the display and touch screen must be flexible and compatible.

- Display technology and material processing – As described in Table 1, limitations exist in the development of transmissive (e.g., LCDs), reflective (e.g., cholesteric displays) and emissive (OLEDs) materials for use in flexible display applications.

- Substrates -- plastic films, flexible glass or metal backplanes – Limitations include gas permeability, lower processing temperatures and mechanical durability with plastic films; impact resistance and flexibility of glass; and transparency and surface roughness for metal foil.

- Resistive touch screen technology – requires the physical contact between two separate, electrically conductive layers. The resistance, caused by the contact of the layers, registers a location on the touch screen. Separation needs to be maintained between top and bottom films while not in use. This is most often accomplished by adding “spacer dots” to one or more of the conductive films. Because resistive touch screens require physical contact for a touch to be registered; a false activation or signal distortion can occur if the touch screen is flexed.

- Projected capacitive (pro-cap) touch screen technology - requires etching of two conductive layers to create an X-Y grid. When a voltage is applied to the grid, a field is created and any time the field is interrupted by a conductor (e.g., human finger), a distortion in the field is noticed by the controller, which is triangulated off the grid and, in turn, a touch is registered. With pro-caps, if the touch input device is not conductive (e.g., a gloved
hand or plastic stylus) the touch screen will not register an input and etching high resolution grids can be more challenging with plastic films.

- Coatings -- Indium tin oxide (ITO), the most common conductive material used in resistive and capacitive touch screens and many displays, will crack when bent or flexed to very small radii. Promising nano-materials such as graphene or carbon nano-tube (CNT) coatings are just becoming widely available for commercial applications and should offer alternatives as the technology matures. Alternative conductive materials (CNTs and silver nano-particles) are generally more flexible than ITO and can be readily patterned. Current market barrier issues that are being addressed include cost, transparency and sheet resistance. Other coatings under development include anti-fingerprint and coatings similar to hydrophobic coatings that improve touch screen aesthetics and “slip” or “feel”.

Table 1. This shows the material limitations exist in the development of transmissive, reflective and emissive materials for use in flexible display applications.

<table>
<thead>
<tr>
<th>Material or Process</th>
<th>Use in Display or Touch Screen</th>
<th>Limitations or Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate – flexible glass</td>
<td>Front surface cover of flexible display or touch screen</td>
<td>Can break, limited flexibility, can be difficult to process roll to roll (R2R)</td>
</tr>
<tr>
<td>Substrate – PET (polyethylene terephthalate)</td>
<td>Front surface of flexible display or front or rear surface of a touch screen</td>
<td>Requires high performance gas barrier coatings to prevent the damage of displays (e.g., OLEDs), relatively low processing temperature may limit some manufacturing processes to be used, birefringent</td>
</tr>
<tr>
<td>Substrate – PEN (polyethylene naphthalate)</td>
<td>Front and rear surface of flexible touch screens and liquid crystal encapsulant in flexible displays</td>
<td>Requires high performance gas barrier coatings to prevent the damage of displays (e.g., OLEDs), relatively low processing temperature may limit some manufacturing processes to be used, birefringent</td>
</tr>
<tr>
<td>ITO coatings</td>
<td>Transparent conductive coatings used in the production of liquid crystals and touch screens</td>
<td>Britteness of ITO may limit use in some flexible display applications, possible material availability issues</td>
</tr>
<tr>
<td>Graphene &amp; CNT coatings</td>
<td>ITO replacement materials used as transparent conductive layer in displays and touch screens</td>
<td>Transmission, resistance, cost and availability may limit near term applications</td>
</tr>
</tbody>
</table>

To address these issues, a variety of new materials, optical coatings, films and manufacturing processes are necessary to aid in the development of flexible displays and improve the mechanical durability and functionality of flexible display and touch screen systems. Coaters and laminators must understand the construction, properties and interaction of various materials used to manufacture flexible touch screens and displays. These include common flexible substrates such as PET (polyethylene terephthalate), PI (polyimide), cellulose triacetate (TAC) and PEN (polyethylene naphthalate); barrier films, thick film surface hard coatings; transparent conductive coatings such as ITO, graphene coatings, and silver nanoparticle and CNT coatings.

it is necessary to understand the types and optical properties of materials, coatings and enhancements necessary to construct and optimize touch screens and flexible display systems (such as OLED and EL) for direct outdoor and demanding environmental applications. In addition to dealing with the environmental, optical and electrical properties, materials and coatings need to be developed, produced and selected for the different levels of flexibility. Authors such as Fihn and Ekkaï² have developed a hierarchy of display and touch screen flexibility as follows:

1) **Rollable** – displays or touch screen can be completely rolled (360 degrees) many times without damaging the screen.
2) **Bendable** – the edges of the display or touch screen can meet many times without damage
3) **Semi-flexible** – the screen can deflect at least 45 degrees many times without damage.
4) **Mostly Rigid** – screen can deflect some, but may sustain damage if bent too far or too often.

5) **Rigid** – uses some flexible materials; however damage most likely will occur if screen is flexed.

6) **Completely Rigid** – screen uses all rigid materials such as glass that can not be flexed without damage. The primary types of flexible displays are shown in Table 2. There are many variations of flexible displays under development in various universities, government labs and R & D centers worldwide. However, touch screen technology presents a larger and more mature market.

**Table 2.** As shown in Table 2, different underlying technologies for flexible displays all come with advantages and disadvantages.

<table>
<thead>
<tr>
<th>Display Type</th>
<th>Description</th>
<th>Attributes</th>
<th>Limitations</th>
<th>Commercialization Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Crystal Display</td>
<td>Full-color high-resolution displays using novel flexible materials</td>
<td>Good resolution, luminance and contrast. Can be equipped with touch sensor for user interface</td>
<td>Requires substitution of plastic materials for glass LC encapsulation</td>
<td>Demonstrated technology (e.g., Toshiba, Fujitsu)</td>
</tr>
<tr>
<td>(transmissive)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Liquid Crystal Display</td>
<td>Medium-color high-resolution displays using novel flexible materials</td>
<td>Good resolution and contrast. Can be equipped with touch sensor for user interface</td>
<td>Requires substitution of plastic materials for LC encapsulation and can be made with metal backplanes</td>
<td>Demonstrated technology</td>
</tr>
<tr>
<td>(reflective)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrophoretic</td>
<td>Typically monochrome electronic paper-type display</td>
<td>Low cost, fairly developed technology. Generally uses PET films</td>
<td>Requires low-temperature processing. Technology has been demonstrated with plastic and metal backplanes</td>
<td>In commercial production (e.g., E Ink, AUO)</td>
</tr>
<tr>
<td>Organic Light Emitting</td>
<td>Color emissive (does not require backlights). AMOLED and OLED technology has been demonstrated</td>
<td>Very good color saturation and viewing angle</td>
<td>Flexible materials used need to have very low oxygen and water permeability. Plastic films require complex transparent high-performance gas barrier coatings.</td>
<td>Demonstrated on low-rate production scale with PEN and PI films (e.g., Sony, Samsung, )</td>
</tr>
<tr>
<td>Diodes (OLEDs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cholesteric</td>
<td>Low-power, monochrome or full color (using three colored layers) graphical. Uses bistable, cholesteric liquid crystals</td>
<td>Low cost does not require polarizers or backlights; is being produced in R2R process; can be activated with electrical current or pressure.</td>
<td>Is not high resolution which limits applications and has slow response times. Limits applications that require high refresh rates (e.g., video).</td>
<td>In commercial production (e.g., Kent Displays)</td>
</tr>
<tr>
<td>Light-Emitting Diodes</td>
<td>Individual LED’s are applied to flexible</td>
<td>Can be very bright</td>
<td>Not high resolution</td>
<td>Demonstrated on small scale</td>
</tr>
<tr>
<td>(LEDs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Materials for Flexible Displays and Touch Screens**

In order to produce the appropriate substrates, coatings, adhesives and other components used in displays and touch screens, material engineers and manufacturers must consider the necessary degree of material flexibility and mechanical, optical and electrical properties. Most commonly, the rigid glass typically used in LCDs and touch screens is replaced with lightweight, transparent, flexible films such as polycarbonate, PEN or PET. As shown in Table 3, the trade-offs for using flexible films instead of glass include inferior photopic properties, lower processing temperature (due to plastic film’s higher coefficient of thermal expansion, which causes potential distortion and lower continuous use temperature),
greater transmission of ultra violet wavelengths, oxygen, and moisture (which will damage OLEDs). The advantages of using flexible substrates include lighter weight, increased impact resistance, and lower material and processing costs. This is especially true for flexible displays and touch screens produced in a high speed roll-to-roll (R2R) process. Most notably, processing and coating technology used to produce optical films in a R2R format is now being used to manufacture flexible electronics, including some displays and touch screens.

### Table 3. The trade offs for using flexible films instead of glass include lower optical transparency, lower processing temperature, high permeability to oxygen and moisture, and softer substrate surfaces.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Visible Light Transmission (VLT) (380 to 780 nm)</th>
<th>Glass Transition Temperature ( (T_g) ) in degrees C</th>
<th>Water vapor Transmission rate at 38˚C, ASTM E-96 Procedure E</th>
<th>Gas Permeability of oxygen</th>
<th>Coefficient of thermal expansion cm/cm x 10^-5/C</th>
<th>Refractive index @ 589 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene terephthalate (PET)*</td>
<td>85-88%</td>
<td>150</td>
<td>&gt;100 (12 mil thickness) to &gt;2,200 (1 mil thickness) cc/in^2/24 hrs</td>
<td>&gt;2.0 (0˚C) to &gt;12 (50˚C) cc/100 in^2/atm/mil</td>
<td>4.32</td>
<td>1.64-1.67</td>
</tr>
<tr>
<td>Borosilicate glass**</td>
<td>91.7%</td>
<td>557</td>
<td>-</td>
<td>-</td>
<td>0.72</td>
<td>1.52</td>
</tr>
</tbody>
</table>

*DuPont Mylar polyester film. **Schott North America D 263 glass.

The obvious advantage of higher throughput R2R processing is somewhat offset by the lower processing temperature and higher potential to induce stress into the films during processing. Common processes used to deposit dielectrics and semiconductor materials in the production of flexible displays include plasma enhanced chemical vapor deposition (PECVD) for silicon oxide or silicon nitride and DC magnetron sputtering for transparent conductive coatings, as well as printed, gravure, or spray for conductive, hard and barrier coatings. Process selection, in addition to material throughput, is typically dictated by the thermal stability, moisture and oxygen sensitivity of the organic and inorganic materials being deposited. In addition, printed electronics require very accurate registration (sometimes as accurate as 1 micron) of materials deposited and removed via photolithography. Due to the relatively high coefficients of thermal expansion of films such as PET and PEN, processing temperature must be controlled in order to minimize the delamination of deposited materials as well as the proper registration of printed circuits and coatings.

In flexible display manufacturing, organic materials are often deposited in a wet chemical process at atmospheric pressures in a combination of a vacuum or sputtering deposition of inorganic conductive metals or metallic oxides. The addition of post-processing films to improve the optical, mechanical or electrical performance of flexible displays includes adding anti-glare or anti-reflective front surface films, conductive films, or optical conductive grids for EMI/RFI shielding. A variety of front surface coatings (e.g., hard, anti-glare hard, specular anti-reflective, hydrophobic and oleophobic coatings) are applied to touch screens and displays to improve durability and functionality. Coated optical films are manufactured using thin film and thick film processes, as well as R2R film lamination.

### Transparent Thin Film Conductive Coatings

In the case of resistive or capacitive touch screens, a patterned conductive coating or grid provides the location of the X, Y coordinates in touch sensor activation. The selection of conductive coatings for flexible display and touch screen fabrication is discussed here in further detail. Key parameters in selecting transparent conductive coatings include photopic transmission and reflection, coating resistance, ability to be patterned, and overall durability.

Transparent thin film conductive coatings offer excellent optical properties on most flexible plastic and glass substrates. A transparent thin film conductive coating is typically deposited onto an optical medium using a high-vacuum coating process (e.g., ion-enhanced e-beam evaporation or DC magnetron sputtering). These high-energy processes can create very dense films. The durability of a specific coating is greatly dependent upon the optical substrate, the specific materials deposited, and the deposition method. The base material of optical plastic substrates often must be treated with
an additional hard-coat layer for the conductive coating to have adequate durability and conductivity properties. As shown in Figure 1, transparent conductive coatings are used as the primary sensor in resistive touch screens.

**Figure 1:** This illustrates a flexible resistive touch screen display assembly.

![Flexible Optical Film](Front) Spacer Dot | ITO | Flexible Optical Film
---|---|---
Front | Rear | Flexible Display

Typical transparent conductive films include transparent conductive oxides (TCOs) such as indium tin oxide (ITO), and metal alloyed films (e.g., alternating layers consisting of Ag (silver) & ITO). In addition to being a key active component to displays (LCDs and OLEDs) and touch screens, transparent conductive coatings are also widely used to attenuate radio frequencies (EMI/RFI shielding) for optical apertures. Increasing the conductivity of the coating will increase the average EMI/RFI attenuation level over the frequency range of 100 KHz through 20 GHz. For shielding purposes, typical conductivities for transparent thin film conductive coatings for this purpose range from 1 Ω/sq. to 100 Ω/sq. Unfortunately, there is an inverse relationship between light transmittance and conductivity. Metal alloyed films offer better cost/performance options over TCOs when applied to plastics. They can be cost effectively deposited in resistances down to 2 Ω/sq. while maintaining moderate total luminous light transmittance performance (i.e., typically >68%Tₜ). The photopic transmission of metallic coatings quickly decreases as the conductivity increases. Although metal alloys have an inferior mechanical and galvanic durability, they are commonly used to reflect heat (e.g., they can greatly reduce the effects from solar loading).

Although TCOs are often costly to apply to plastics for resistances below 30 Ω/sq., they can be applied to glass to values below 1 Ω/sq. A low resistance coating on glass will offer high performance but cost more (on a per sq. in. basis) because it is deposited in a batch vacuum process rather than a web or continuous process. Additionally, to enhance visible light transmission, most TCOs can be fully integrated into a multi-layer dielectric stack as part of a broadband anti-reflection (AR) coating. An AR coating reduces surface reflection losses and increases transmitted light. A fully enhanced TCO can have a total luminous reflection of a broadband white light source (e.g., illuminant D₆₅) of less than 0.5%. Furthermore, the photopic absorption of TCOs tends to be very low, often less than a few percent at fairly high conductivities (i.e., <10 Ω/sq.). High transmissivity and low reflection of the materials used to construct the display/touch screen generally equates to higher display system luminance and efficiency. These features are important to optimize display system viewability.

**ITO Replacement Coatings**

ITO is the current leading transparent conductor used in displays and touch screens due to its high-performing optical, electrical, and durability properties. However, the market growth of ITO replacement materials is occurring due to a variety of factors. Indium, the dominate component of ITO, has a potentially limited availability and, as such, is subject to price volatility. It is also a brittle ceramic material and therefore it is not ideally suited for flexible electronics. Typically, ITO is deposited via CVD, sputtering or vacuum deposition processes, which are usually costly compared to other deposition methods. So, materials such as silver conductive inks (for grid and irregular patterns), graphene, PEDOT-PSS, and other CNT-based conductive coatings are being developed and commercialized by a variety of organizations and companies as possible solutions to the limitations of ITO.

For flexible electronics, these materials offer the potential of greater durability when subjected to repeated bending. In order to offer a viable ITO replacement material, CNTs or silver conductive inks (or silver nanowires) must provide
optical transparency in the range of 85% to 90% and sheet resistance in the 10 to 400 ohms/sq. range. The conductive layers of most resistive touch screens are in the ranges of 200 to 500 ohms/sq. For most flexible displays, the conductive layers are in the ranges of 1-50 ohms/sq. In addition, the CNTs and silver nano-wires must provide a material or processing cost advantage. ITO coated films, with a cost range of $10.00 - $40.00 meter$^2$, are currently less expensive than most carbon or silver based nano coatings. This may be partially due to the scale or production volume of ITO coatings compared to the alternative materials. This scenario is expected to change over the next few years, however, with the advent of more efficient and larger format R2R processing in the production of nano materials. Current CNT coated films offer a coating resistance in the range of 300 to 450 ohms/sq. with a transparency of 82%, which makes them viable candidate as an ITO replacement material for many touch screens. Silver nano-particle based transparent conductive coatings and grids can produce a sheet resistance of < 20 ohms/sq., allowing them to be used as flexible display conductors.

Because touch screens are active user interface devices, both surface coatings (typically coated with clear/no anti-glare properties or anti-glare hard coatings) and internal thin film conductive coatings must be suitability durable to withstand a million or more touches.

**Materials for Enhanced Displays and Touch Screens**

The optical performance of displays and touch screens is very important, especially in high ambient light conditions. Reflections occur at interfaces where light transfers from one medium to another due to refractive index changes. Resistive touch screens have four major interfaces, each of which either goes from air to an optical medium or, conversely, from an optical medium to air. Reflection problems are further compounded because the resistive touch screen is comprised of plastic substrates with hard coatings and thin film coatings on flexible optical materials that create additional material interfaces and sources of reflection. A better understanding of the cumulative effects of surface reflections can be attained using the Fresnel equation shown here:

Equation 1: \( R = R_s = R_p = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \) (Fresnel Equation for normal reflections)

When applied for normal incident light to the first surface interface where the initial medium is air \( n_1 = 1.0 \) and the exit medium is an acrylic hard coating \( n_2 = 1.5 \), the result is a value of 4% for the first surface reflection. The reflection increases when evaluating the first internal layer due to refractive index differences between the conductive thin film coating (i.e., the active conductive layer inside the touch screen, which typically has an index >2.0) and air. This can be improved somewhat by partially “index matching” the conductive coatings (e.g., adding dielectric layers to the thin film stack, which lowers overall reflections by creating destructive reflections). (Just curious: what are “destructive reflections”?) For resistive touch screens, limitations exist with index matching because the outer internal layers of the touch screen must remain conductive and, currently, there are no low index conductors. Figure 2 provides a basic surface reflection summary of a typical resistive touch screen. As shown, because the total luminous reflection of a “Commercial Off The Shelf” (COTS) touch screen can exceed 24%, contrast and, therefore, high ambient readability is compromised if these issues are not addressed.
Design Considerations – Optical Enhancements to Touch Screens

In order to reduce the surface reflections in a touch screen display system, each interface must be considered. By applying an anti-reflective coating on both the front and rear surfaces, surface reflections can be reduced by approximately 6.5% (reducing the inherent 4% reflection per surface to less than 0.75%). There is a wide range of internal reflections in COTS touch screens (i.e., < 2% to > 8% per interface) which is mostly dependent on the specific transparent conductive coatings utilized. A thin film anti-reflective coating cannot be directly deposited in a vacuum to the completed COTS resistive touch screen. The deposition process would cause the air gap between the flexible membrane and the spacer dots to collapse. This would result in varying degrees of plastic deformation around the spacers and the degradation of the touch screen’s optical and electrical integrity. For this reason, it is common to apply a conductive coating to a thin optical substrate and then to laminate it onto the outer surface of the touch screen. The most cost effective lamination is a flexible film lamination (0.003 in. to 0.009 in. in total thickness) to one or both surfaces of the touch screen. Common optical substrates include PET, TAC, and glass (in the case of the rear surface of a rigid touch screen). The flexible substrates are commonly hard coated with acrylic or silane-based hard coatings to improve mechanical durability and to add anti-glare properties in order to scatter specularly reflected light. Considerations for carrier film selection are index of refraction, durability, cost and birefringent properties.

Optically coupling the rear surface of the touch screen with the front surface of the display using an index match bonding adhesive is becoming an increasingly popular method to improve high ambient light readability. Optical bonding eliminates two reflective surfaces, thereby increasing contrast. Additional benefits include elimination of space where condensation can occur and better shock and vibration performance.

Internal reflections, ambient light reflected from the front surface of the display or rear surface of the touch screen, will reduce contrast and viewability. To address this issue, a circular polarizer (CP) can be integrated into the front surface membrane of the resistive touch screen to suppress the internal reflections of the touch screen. The CP is a linear polarizer combined with a ¼ wave retarder. A CP can eliminate over 99% of internal reflections by introducing a phase shift of the orthogonal components of the polarized light that is reflected off the internal layers of the touch screen.

By minimizing reflection loss, contrast and high ambient readability of the display is greatly increased. When integrating a CP into a touch screen, the polarization angle must be aligned with the polarization angle of the display. In addition, birefringent materials used in touch screen construction (i.e., PET) will interfere with the function of the CP and should be eliminated from the design.
It should be noted that other touch screen technologies, such as infrared touch screens and emerging optical touch screen technology based on sensors, eliminate the need for transparent conductive materials entirely. As such, optical touch screens could be a good candidate for the emerging flexible display/touch screen market.

**Conclusion:**

The growth in applications for flexible displays with touch screens is being driven by the market demand for lighter, less costly and more functional user interface devices. In addition to the material and process technologies used in the fabrication, flexible electronics can be applied to other emerging markets such as photovoltaics, smart cards and solid state lighting. There is a growing need for coated durable flexible plastics with optical and durability properties similar to that of coated glass. Consequently, rapid market growth is forecasted for transparent conductive films and materials such as ITO, CNT and silver nano coatings used in the production of flexible displays and touch screens. Additionally, higher durability hard coatings with better optical properties are needed as well as better, low-cost, low-permeability barrier coatings. In all cases, the developed plastic films would ideally have all of the positive attributes of glass while maintaining the desirable flexible properties of a plastic film.

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