High-Performance Plastic Substrates for Flexible Flat Panel Displays

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Abstract
New high-temperature (Tg>300 ºC) optical polymers are under development by Ferrania S.p.A and Promerus, LLC. Substrates based on these materials demonstrate excellent chemical resistance, low O_2 permeability and superb physical and optical properties. These properties offer the potential of meeting the requirements for roll-to-roll processing of flat panel displays.

1. Objective and Background
The proliferation of electronic devices in our personal and professional lives has driven research into flat-panel displays (FPDs) that are smaller in size, lighter in weight, more rugged, cost effective and energy efficient than previous designs. Although liquid crystal displays (LCDs) - both transmissive and reflective – remain the dominant technology, the interest in organic light emitting diode (OLED) has been growing rapidly in recent years [1],[2]. Compared with LCDs, OLEDs use an emissive technology, thus offers superior viewing angles and contrast ratios, faster response time, lower power consumption, and ultimately thinner, lighter and more flexible displays. Because virtually all organic materials used in OLEDs are held together by highly flexible van der Waals interactions, OLED technology is the first technology with the potential to be highly functional and durable in a flexible format. Thus the recent advances in OLED technology reinforce the interest in the use of plastic substrates for making flexible flat panel displays, light sensors and other electronic products.

Unlike glass, the current primary medium for FPDs, plastic is usually more robust and compact, has lighter weight, and is more cost effective. Fabrication of displays on a thin flexible sheet of plastic leads to a durable, lightweight product suitable for many applications in the growing market of pagers, cell phones, and personal digital assistants (PDAs), as well as a number of new, and as yet, unrealized product opportunities, such as foldable displays, smart cards, all plastic electronics, and portable or conformable displays that may be affixed to windows, windshields and instrument panels. The use of plastic substrates also enables greater design freedom by use of non-rectangular and non-planar displays, and potential for economical, efficient, high-volume manufacture incorporating roll-to-roll processing.

Because of these advantages, in the last decade, plastic substrates have been used in passive- and active-matrix LCDs [3],[4], as well as OLEDs [5],[6]. Most often used plastics for FPD include polycarbonate (PC), polyester (PET), polyethersulfone (PES), and polyimide (PI). While it is a very promising new technology, these plastic substrates are limited by either low processing temperature, high heat-induced shrinkage, high gas permeability, low chemical resistance, average water/solvent durability, or average transparency. The current market trend of FPDs points to displays having active-matrix thin-film-transistor (TFT) addressing to achieve good contrast and reliability [7],[8]. The next-generation displays, both LCDs and OLEDs, will most likely be produced on flexible substrates with integrated display-driver circuitry [6],[7]. Temperatures greater than 250 ºC are needed to achieve good device performance (drive currents of about 1 mA) and reliability that are necessary for monolithic integration of low-power CMOS display-driver circuitry. The ideal substrate for active matrix LCDs and OLEDs would combine the barrier, thermal and scratch resistant properties of glass with the flexibility, toughness and processability of plastic [9],[10]. The future display market calls for a new generation of plastic materials.

Promerus LLC and Ferrania Imaging Technologies have years of experience with high-temperature polymers. Based on our proprietary polynorbornene [11] and polyarylate [12],[13] technologies, we have developed two classes of amorphous, high-temperature (Tg>300 ºC) optical polymeric materials, Appear 3000 and AryLite. The materials exhibit excellent optical, thermal and mechanical properties. Multi-layer engineered substrates have been designed to ensure good chemical/scratch

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resistance and low oxygen/moisture permeability. The combination of these attributes offers the potential of these substrates in economic fabrication of high-performance of active matrix LCD and OLED devices by continuous (roll-to-roll) processing and the potential of back integration of such materials into the manufacturing of existing passive matrix LCD and cholesteric systems resulting in new life for these established technologies.

Manufacturing of these engineered substrates (base film coated with hardcoat, barrier coat and ITO) has been demonstrated on a continuous film line. Further efforts are needed to carry this demonstration toward actual production of functioning devices.

2. Results

In order to be used in FPDs, especially LCDs and OLEDs, flexible substrates must possess a number of performance characteristics. These include very low oxygen and moisture permeability, very smooth surface, good chemical and thermal resistance required in FPD processes, excellent optical clarity and transparency, low retardation and cost that is comparable to or lower than glass substrates [9]. Appear 3000 and AryLite have demonstrated to meet all these requirements.

2.1 Base and Hardcoated Film

Properties of the hardcoated films are summarized in Table 1. These films are light in weight and durable. They have good thermal and mechanical properties. Optically, they are highly transparent in the visible range and have low retardation. They are made on a continuous film line and exhibit excellent moisture/solvent resistance. We have also studied dimensional stability of Appear 3000 and AryLite in a standard semiconductor processing. The results are shown in Figure 1. The accumulative dimensional changes, after the 7 processing steps, of Appear 3000 and AryLite are -0.003% and 0.000%, respectively.

Thermal compaction rate of polymers is important for successful manufacturing of TFTs on these substrates. Substrates having a shrinkage rate of <3 ppm/hr ensure accurate registration between steps (i.e., a movement of <1 µm over an entire 12”x12” display). The dimensional stability of hardcoated Appear 3000 and AryLite have been measured at temperatures of interest (e.g., 250 ºC, 275 ºC, and 300 ºC). The results at 300 ºC are shown in Figure 2. In general, both films reach the target shrinkage rate (3 ppm/hr) after ~50 hours of baking at 250-300 ºC under vacuum (1 mTorr) without unacceptable degradation in color. As a comparison, Kapton requires twice as much time to reach the same target rate.

2.2 Barrier Layer and ITO

The barrier coating, an inorganic-organic hybrid material, is applied onto the hardcoated film to improve oxygen and moisture permeability of the plastic film. ITO is the outermost layer to increase surface conductivity. Typical values for ITO conductivity and optical transmission of an ITO coated substrate are 50 ohm/sq and >82% averaged between 400 and 700 nm, respectively. Recent results on barrier coated Appear 3000 demonstrate an oxygen transmission rate of <0.005 cc/m^2/day.atm (100% oxygen, 0%RH, 23 ºC).

2.3 LCD Displays Fabricated Using Appear 3000

Liquid crystal displays were fabricated using Appear 3000. These displays exhibit electro-optical characteristics equal to glass displays. Both segmented TN and graphics STN style displays were designed and assembled using a novel composite polymer/liquid crystal structure [14]. The composite structure resulted in cell gaps with uniformity better than 0.2 microns repeatably with high yields. The 96x65 pixel (pixel pitch - 0.35 mm) STN display is shown in figure 3. The display is driven by a standard LCD controller (Hitachi Inc.). The composite structure is capable of maintaining the cell gap under both compressive, shear and peel forces resulting in a display whose minimum operating bend radius is 2 cm and compression resistance is greater than 4.5 kg/cm.

Table 1. Properties of Appear 3000 and AryLite Films

	Appear 3000	AryLite
Thermal		
Tg	330 ºC	325 ºC
Decomposition temperature (at 5 wt% loss)	360 ºC	480 ºC
CTE (-55 to 85 ºC)	74	53
Flammability (UL94)	Burning rate >HB	V-0
Optical		
%Transmission (400-700 nm)	91.6%	90.4%
Refractive index (633 nm)		
base	1.52	1.64
coating	1.51	1.51
Retardation (100µm-thick film)	<10 nm	<10 nm
50% Cutoff wavelength	330 nm	360 nm
Physical		
Young’s modulus	1.9 GPa	2.9 GPa
Tensile strength	50 MPa	100 MPa
Elongation to break	10%	17%
Specific gravity	1.16	1.22
Water absorption	0.03%	0.4%
Electrical		
Volume resistivity (ohm.cm)	3.2×10^{16}	8.0×10^{16}
Surface resistivity (ohm/sq)	7.9×10^{15}	2.3×10^{17}
Dielectric constant (1 MHz)	4.1	3.4
Loss tangent (1 MHz)	8.7×10^{-3}	9.0×10^{-3}
Chemical resistance: both substrates resist all of the chemicals specified as follows: NMP, IPA, Acetone, Toluene, Methanol, Ethanol, THF, Ethylacetate, HMDS, H_2O, HCl-37%, H_2SO_4-98%, HNO_3-70%, H_3PO_4-85%, HBr-48%, CH_3COOH-glacial, $FeCl_3$, KH_2PO_4, H_2O_2-30%, sat. Na_2CO_3, sat. NaOH and sat. KOH.		

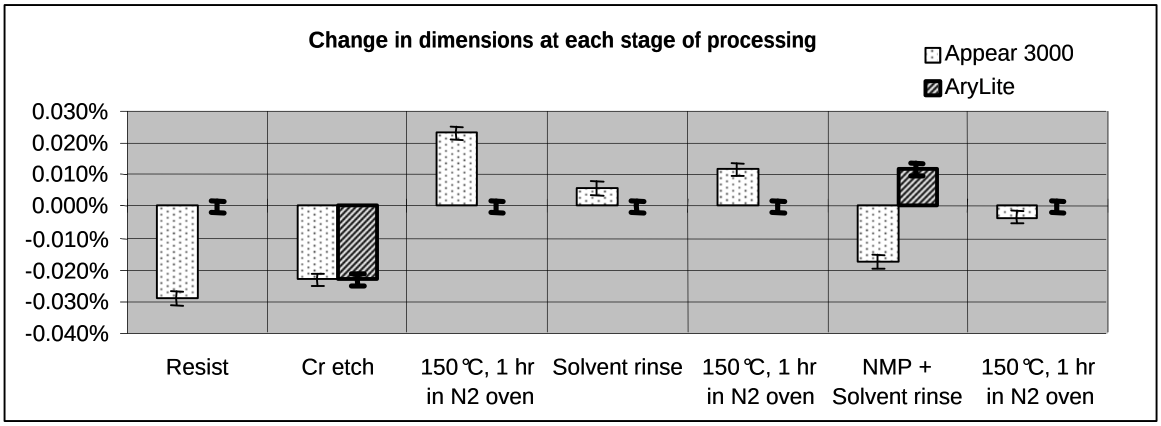

Figure 1. Dimensional changes of Appear 3000 and AryLite in a representative semiconductor process

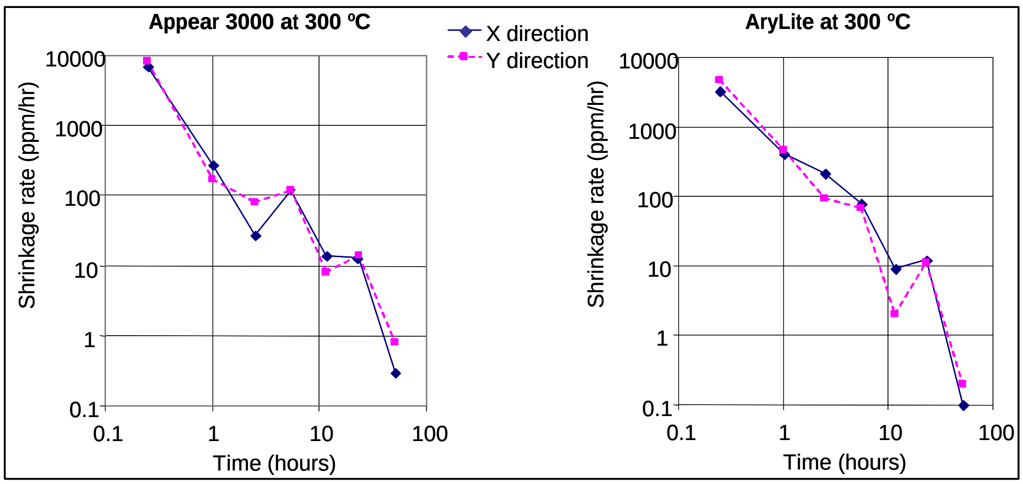

Figure 2. Thermal compaction of Appear 3000 and AryLite at 300 ºC, 1 mTorr.

Contrast for the TN cell was measured at greater than 200:1 with response times of less than 4 ms. The total display thickness was 0.3 mm, including polarizers. Preliminary results with Arylite indicate that Arylite-substrate displays will be of equal performance.

3. Conclusions and Impact

Promerus LLC and Ferrania Imaging Technologies have successfully developed a set of high-temperature films for plastic substrates in the flat panel display market. The engineered substrates consist of a minimum of 4 layers, base film, hardcoat, barrier coat and ITO. These substrates are being manufactured by solvent casting in a continuous process. The current preferred substrates exhibit low retardation (1-8 nm), wide spectral window (400-700 nm), high glass transition temperature (>320 ºC), and low moisture absorption (0.03-0.4%). Furthermore, they have been demonstrated to have good mechanical and electrical properties, as well as low oxygen permeability and superb chemical resistance (resist common chemicals, such as NMP, Acetone, IPA, Toluene, conc. HNO_3, conc. H_3PO_4, sat. KOH, etc.). Further optimization of these engineered substrates is still in progress. We believe these substrates open up the potential for low-cost production of flexible, lightweight, active-matrix LCDs and OLEDs on a roll-to-roll basis.

Figure 3. Flexible 96x65 pixel 1.5 inch diagonal monochrome STN display manufactured by Viztec Inc.

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