5.1.1 Glass Substrates for AMLCD, OLED and Emerging Display Platforms

Peter L. Bocko

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Abstract: The properties of today's glass substrates for AMLCDs, OLEDs, and emerging display platforms have resulted from decades of collaboration between display manufacturers and the glass industry. The development of flat panel applications led to display manufacturing platform innovations which, in turn, have driven glass composition and substrate design. This article discusses basic glass technology and substrate innovation as influenced by the evolution of the display industry. It begins with a description of the principal display applications and an overview of the active platforms employed to meet the requirements of those applications amorphous silicon, polysilicon, organic light emitting diodes, and reflective bi stable including brief statements of the key challenges to substrate manufacturers engendered by each platform. Substrate requirements including glass composition, surface quality, advanced physical attributes, and other factors for each of the active matrix platforms are discussed. Because glass is increasingly employed as a structural and design element of the display device, the article closes with a discussion of glass reliability within the context of display centric information appliances.

List of Abbreviations: *AMLCD,* Active Matrix Liquid Crystal Display; *a Si,* Amorphous Silicon; *CF,* Color Filter; *CTE,* Coefficient of Thermal Expansion; *DOL,* Depth of Layer; *Gen,* Generation (of Glass Substrate); *LCD,* Liquid Crystal Display; *LTPS,* Low Temperature Polysilicon; *OLED,* Organic Light Emitting Diode; *PMMA,* Poly(Methyl Methacrylate); *p Si,* Polysilicon; *TFT,* Thin Film Transistor

1 Introduction

In considering the development of glass substrates for active matrix liquid crystal displays (AMLCDs), the primary factor driving substrate design was the emerging needs of the application and the manufacturing processes developed to meet the device performance. Essentially, the glass design process must be considered as an intrinsic part of the display platform development. Thus, substrate properties have been and continue to be defined through a true collaboration between display manufacturers and the glass industry as the liquid crystal display (LCD) platform has evolved through successive waves of applications.

2 Substrate Innovation in Response to Display Applications

Innovation in display substrates has been driven largely by the requirements of four applica tions: notebook computers, desktop monitors, televisions, and high performance portable devices. An emerging application, e Paper, is likely to bring its own requirements, as well.

2.1 Notebook Computer

As the first high volume application for AMLCD, notebook computers demanded portability and operation from battery power; therefore, LCD's low voltage operation made it the only practical choice for this application. The key requirements for glass substrates used in the development of the notebook computer application were the ability to withstand elevated temperatures (as high as 450°C) without deformation, the ability to withstand the harsh and

diverse chemical environment of the early AMLCD process, and a surface quality (freedom from particulate contamination and scratches) consistent with achieving acceptable yields in the manufacturing process. During the early development of the notebook computer, screen dimensions were relatively small (8.5 10.4″ diagonal measure). With glass substrates correspondingly small (approximately 300 × 400 mm), panel size was not a focus in AMLCD glass substrate development.

2.2 Desktop Monitor

The next wave of application growth was the displacement of the cathode ray tube (CRT) in the desktop computer monitor application. Adapting the LCD platform for this use required a major scale up of the panel size (up to approximately 20″). Unlike notebooks, where the uniqueness of a thin and light form factor brought value, the desktop monitor had to be economical enough to replace a CRT while simultaneously delivering compelling on screen performance. The need for large screens manufactured at lower cost drove innovation in glass substrate size. Trends to higher resolution and implementation of wide viewing angle technologies required continuous improvement of dimensional attributes, such as substrate stress and thickness control.

2.3 Television

Television serves as a social congregator, bringing people together for entertainment and information. This fact has driven further innovation in AMLCD viewing performance, addressing the so called LCD legacy issues of viewing angle and pixel response speed that were of lesser importance in Information Technology applications. The neutralization of legacy issues through advanced liquid crystal modes and novel array design drove base substrate sheet characteristics (such as thickness tolerance and surface quality) to even higher levels of performance. Critical, as well, was the scalability of the substrate to dimensions as large as 3 m and the substrate's compatibility with large size manufacturing processes.

The trend to new content will continue to drive demand for improved LCD TV performance. Applications such as interactive gaming and digital workspaces bring users closer to the display, creating a need for higher resolution, larger displays, and new forms of interaction, including multi touch capability. As movie studios, sports networks, and live concert venues realize the potential for stereoscopic 3 D, more high value content will be available, creating a demand for 3 D in the home. Generally, a television capable of a compelling 3 D experience must be larger, higher resolution, and brighter than a television used only for 2 D content. The multiplicity of approaches to adapt LCD TV for 3 D will make the implications to the substrate, beyond simply sustaining existing attribute trends, difficult to predict.

2.4 Portable Device

This category, which comprises a broad range of devices used for personal entertainment and information by an individual rather than a group, includes cell phones, camera phones, navigation systems, mobile TV, video phones, and personal music or video players.

These displays must be robust, vivid, and rugged. Therefore, for the first time, the strength of the substrate became a critical design criterion as the panel dimensions increased (even while becoming thinner) and touch functionality was incorporated. Portable devices achieve a premium based upon low power consumption (long battery life), better picture quality, and thinner form factor. Glass attributes for portable devices include thinness, high temperature capability for advanced array processing, high strength, and very precise thickness control to enable smaller design rules versus larger displays.

2.5 e-Paper

e Paper is an emerging application (see Sect. 8, Paper Like and Low Power Displays) for which performance trends in glass are yet to develop. At a minimum, e Paper will require extremely low power consumption, thin and light form factor, and a paper like reading experience. Flexibility is also expected as a requirement for high value applications. Thus far, e Paper has been limited to e books, which are essentially hybrid devices leveraging existing LCD capabilities for the backplane (amorphous silicon [a Si] on glass substrate) and electro optic front plane polymer composites. Although it is too early to say what the role of glass will be for this application as new technologies such as organic semiconductors are adapted, substrates will most likely need to be thin, light, strong, and compatible with low cost manufacturing and therefore possibly flexible. Options for low cost manufacture for flexible e Paper include roll to roll processing [1]. Materials that are routinely processed in roll form, such as polymer or metal [2] would seem to be more practical choices for flexible display. Yet thin glass brings a number of advantages over other flexible materials in the dimensions of transparency, high dimensional stability, and superior surface [3], and thin flexible glass is also a feasible option for roll to roll processing [4].

3 Manufacturing Platforms Employed to Meet the Requirements of Display Applications

The manufacturing platforms employed in the aforementioned display applications include amorphous silicon, polysilicon, organic light emitting diodes, and bi stable reflective. Amor phous and polysilicon each brought specific performance challenges to the substrate challenges that have created an emphasis upon a subset of possible substrate attributes as the backplane technology and substrate evolved to the highly optimized platform. Understanding the optimi zation of the glass substrate therefore has a strong historical component. In the emerging platforms of organic light emitting diode (OLED) and bi stable reflective displays, it is reason able to expect the same dynamic.

3.1 Amorphous Silicon LCD

The versatility and extraordinary scalability of the amorphous silicon LCD (a Si) platform have made it the dominant technology in notebook computer, desktop monitor, and TV applica tions. This, despite the fact that in the early days of LCD development a Si was considered, at best, a temporary solution until polycrystalline silicon with its higher semiconductor

performance could be industrialized. Additional details on the amorphous silicon platform may be found elsewhere in this encyclopedia (Chap. 5.2.1).

The first thin film layer deposited on the substrate in the preferred embodiment of a Si (known as the bottom gate thin film transistor [TFT]) is the gate line. The earliest industri alized TFTs employed refractory metal gate lines, including chromium, tantalum, molybde num, and a variety of alloys. This choice drove the optimization of two attributes of a Si glass substrates: durability to corrosive chemicals (to etch the gate line without unduly damaging the glass surface) and mechanical strength of the surface (required because of the impact of high levels of intrinsic stress in the refractory gate metal and their impact on glass surface reliability). Also, the processing temperatures of a Si, which originally exceeded 450°C, as required by the deposition of a high quality gate insulator, drove the adoption of glasses with high temperature capability. Although aluminum alloys have largely replaced the problematic refractory metals, and channel processing temperatures have been reduced to approximately 300°C, highly durable and high temperature glasses have remained the standard because of their benefits for a robust processing window.

3.2 Polysilicon LCD: p-Si

After a protracted development, p Si is now a leading platform in the high performance portable device application. In p Si's most common backplane design, the top gate design, the channel of the TFT device is in more intimate contact with the substrate surface (usually with a thin film oxide buffer layer interposed) than in most a Si backplanes. Thus, the substrate surface can have a more profound impact on the transistor characteristic. Substrates for p Si must deliver the highest level of surface quality among display substrates. For example, surface contamination must be monitored and controlled in the sub micron regime. In addition, the p Si process often requires steps that exceed 600 700°C (such as activation following ion implantation) and potentially even higher; therefore, the core challenge for the substrate industry is in achieving dimensional stability at these high temperatures. Additional details on the polysilicon platform may be found elsewhere in this encyclopedia (Chap. 5.2.2).

3.3 Organic Light-Emitting Diode (OLED)

OLED devices share backplane technologies adapted from LCD, especially polysilicon, because OLEDs' current driven operation is effectively served by p Si. The substrate properties for OLED have not yet significantly diverged from those of polysilicon LCD because OLEDs are primarily a high performance option for the portable application. However, this may change because OLED (see Part 6.6) is seen as having some potential in the TV application, where the processes required to scale to large size will drive substrate innovation in the dimensions of thermal and surface quality dimensions.

3.4 Reflective Bi-stable

The low energy consumption requirement of e Paper has stimulated a variety of candidate systems in which an electro optic mechanism, including certain modes of liquid crystal, results

in a change of reflective state. At the early stage of development, the electrophoretic display, which uses electrophoresis to switch pixels between a light and dark state, appears to have an early lead. However, as is the case for e Paper, it is too early to predict the impact on substrates of the future for this segment of displays.

4 Glass Substrate Requirements for AMLCD

4.1 Amorphous Silicon (a-Si) LCD

In this subsection, glass composition criteria and substrate dimensional performance factors are discussed.

4.1.1 Glass Composition Requirements for a-Si LCD

Virtually all of the a Si LCD substrates today belong to the old and extremely versatile glass composition family of alkaline earth aluminosilicate glass systems. The chemistry of this glass family has delivered the key performance criteria of control of alkali contamination, low density, low thermal expansion, and thermo mechanical reliability [5, 6].

Control of Alkali Contamination

Although glassmakers recognized that sodium could be detrimental to thin film electronic functionality, early experiments indicated that perhaps a low level of alkali could be tolerated in the LCD substrate, provided the glass were of sufficient chemical durability [7]. However, during the active matrix technology development, even a small amount of sodium was seen as problematic given the experience of sodium as a contaminant in the semiconductor industry. This motivated the reduction of sodium to trace levels in glass melting processes to prevent the numerous performance and reliability issues that were feared. However, in a conventionally melted glass it is impractical to drive sodium to the part per billion level normally associated with semiconductor devices. Why have not the low but measureable tramp levels of sodium caused issues in LCD? Part of the reason is the adoption of silicon nitride as the gate dielectric in a Si TFT as well as barrier films in p Si. However, other factors may have contributed to this.

Sodium out diffusion from the glass into the liquid crystal device can result from inter diffusion (i.e., exchange) of sodium in the glass with hydrogen ions that may be present as water in the device or environment. Hydrogen exchange maintains charge neutrality when the sodium moves, and one would expect that there would be a driving force for sodium to move from the high concentration of the glass (which may be of the order 10^2 10^3 ppm) to the lower concentration in the LCD device. However, it has been observed that for LCD aluminosilicate glass, the presence of boron and aluminum may suppress the out diffusion of sodium. The aluminum and boron ions in the glass can change from three to four coordinates in the presence of charge compensating cations, thus acting as a potential sink for alkali [8].

Today's LCD glass still has sodium levels of about 100 ppm, but because of the stabilizing effect of the aluminosilicate glass structure of LCD substrates, sodium contamination has not been an issue.

Low Density

The adoption of low density glass contributed to achieving low device weight targets for portable applications. It also resulted in more facile robotic handling during high speed automation because of reduced sag of low density glass.

Sag is the deflection of the glass substrate due to gravity. Sag of an elastic material is proportional to

$$S \propto L^4 \rho g \left(1 - v^2\right) / t^2 E$$

where S is the sag, L is the unsupported span, ρ is the density, g is the gravitational constant, v is Poisson's ratio, t is the thickness, and E is Young's modulus.

Gravimetric sag was a special challenge in the adoption of large sizes because equipment manufacturers had not yet learned how to support the substrate from the back side of the glass (thereby reducing the unsupported span) without inducing damage. The introduction of lower density glasses therefore helped facilitate the evolution to larger substrate sizes.

Low Thermal Expansion

Low coefficient of thermal expansion (CTE) brought several benefits, including reduced breakage due to thermal shock or gradients and minimizing dimensional distortion during transient thermal steps [9]. One manifestation of the beneficial impact of low thermal expansion is the impact of thermal gradients within the plane of the substrate during process steps. The lowest expansion substrate glass, when exposed to a thermal gradient, will have the lowest nonlinearity of the relative positions of features on the glass. It was this effect that caused early notebook innovators to adapt designs that had a high tolerance to these dimensional distortions. The adoption of low expansion glass therefore facilitated the development of brighter displays and longer battery life by increasing the aperture ratio of the displays. In fact, the 80% aperture ratio milestone for notebook computers was first achieved by improved TFT design and employing a glass with a CTE of less than 4 ppm/K.

Thermal Stability

One of the defining criteria that distinguish glass from crystalline material is glass's lack of a discontinuity of physical properties (such as density and viscosity) between the solid and liquid phases. Instead, the physical properties of glass are highly affected by relaxation of its structure in its transition region very roughly defined by the temperature range in which stress is relaxed in the glass from a timescale of minutes to several hours. Therefore, the structure of the glass and its key physical properties are highly dependent upon its thermal history in addition to its composition. A glass article cooled rapidly from the liquid state (i.e., quenched) results in a lower density than one cooled more slowly because of the lack of time for structural relaxation to the denser and lower energy structure. Moreover, when a glass substrate is subjected to higher temperatures, such as those employed in a TFT process, relaxation can cause significant dimensional changes in high temperature processes that need to be managed or compensated for, namely, thermal shrinkage and thermal sag.

Thermal shrinkage is caused by viscous relaxation within the plane of the substrate, causing permanent dimensional change. The TFT process can be simply characterized as several cycles of film deposition or other steps at elevated temperature followed by photolithographic patterning. Shrinkage on the order of 1 3 μm, significant enough to cause a pattern error between successive photolithographic exposures in a TFT process, can be observed in

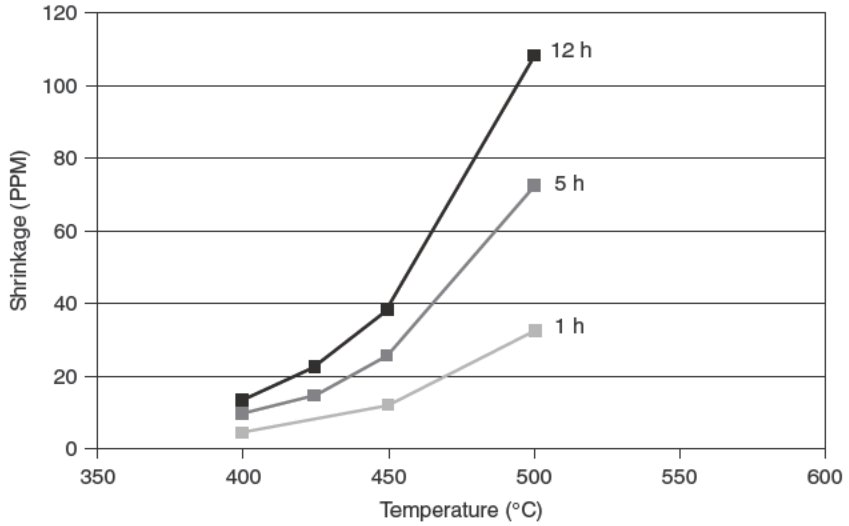

Fig. 1
Shrinkage of a typical a-Si substrate in the 400 500°C range. The transition range of this glass is above 650 800°C (Courtesy of Corning Inc.)

a substrate when process steps occur even several hundred degrees below the transition region of glass. *Figure 1* shows shrinkage of a typical a Si glass as a function of temperature and time at temperatures above that of a typical a Si process but well below the transition region of the glass [10].

While the TFT process can employ magnification during photolithographic exposure to compensate for the movement of thin film features due to thermal shrinkage, this has practical limitations. For production lithographic equipment, the limit for compensation of absolute thermal shrinkage should generally be in the range of 10 20 ppm. Also, the thermal shrinkage must be both isotropic and uniform within the sheet.

Thermal sag is a permanent deformation of the substrate due to the effects of gravity combined with viscous relaxation of the glass as it experiences a thermal treatment while held horizontally. Thermal sag can result in difficulty in robotic handling of the sheet. One particular handling issue that can be an outcome of thermal sag is the inability of the sheet to be vacuum chucked into flatness on a photolithography stage.

The glassmaker has two options for reducing thermal shrinkage and sag in order to meet the requirements of the TFT process. The first is to control the tendency of the glass to thermal relaxation at elevated temperature, in effect stabilizing or "pre shrinking" the glass by adding an additional high temperature pre treatment step. The other is to design the glass composition for intrinsic thermal durability by increasing the glass high temperature viscosity. The aluminosilicate glass system is particularly suited for design of high thermal stability glasses for AMLCD applications; however, a practical consequence and challenge for the glass manufacturer is correspondingly higher temperatures required in glass manufacture.

Strength and Fatigue Resistance

Strength is that value of mechanical stress causing glass to break. If the glass is of high quality, that is, pristine and without defects, the strength of glass will approach 14 GPa, which is higher

than any other material. Unfortunately, AMLCD substrates' glass surfaces are exposed to imperfections during manufacturing, finishing, handling, and in the TFT process which induce flaws and reduce their strength. Defining in absolute terms the mechanical reliability of an AMLCD glass substrate in the application is problematic; strength of a substrate is not an intrinsic property of its composition alone but is highly dependent upon the flaw size distribution and the testing method.

However, an intrinsic property of the glass composition is its fatigue resistance, which has a profound effect upon the long term reliability of the glass under stress [11]. The glass fatigue mechanism impacts several aspects of the AMLCD application. The strength of the panel under long term stress (whether structural mechanical stress in the device or the small scale stress exerted on the glass surface by adherent films) is enhanced by the use of fatigue resistant compositions. Aluminosilicate AMLCD substrates of today have fatigue resistance 40 60% higher than that of soda lime glass [12]. Glasses with high fatigue resistance can be cut more reliably in back end processes of panel manufacture [13].

4.1.2 Surface Quality Requirements

Substrate Flatness

Deviation of the substrate surface from a perfect plane on a range of scale from a few microns to the full dimension of the substrate (several meters) has potential impact on a variety of aspects in AMLCD processing and device performance. Collectively, the deviation of the substrate surface is imprecisely termed "flatness" with contributions arising from variation of the substrate thickness at all scales as well as bending ("warp" or "shape") of the sheet. As process and device design have evolved in the AMLCD platform to achieve increased productivity and display performance, substrate quality attributes in the flatness regime likewise have become more tightly controlled.

Table 1 illustrates the trend in glass sheet quality attribute at two points in AMLCD evolution. Commonly used terminology for deviation of a substrate from a plane is used in this table; admittedly these terms, non standardized in the glass industry, are imprecise. When characterizing a substrate requirement in an aspect of flatness, it is important to define the dimensional scale at which the deviation is manifested.

Table 1

AMLCD substrate flatness performance trend in sheet attributes. Attributes are defined by the typical required deviation as well as the dimensional scale at which the deviation occurs

Year	1995	2010
AMLCD generation	Gen 2	Gen 10
Substrate size	37 × 47 cm (approx)	288 × 313 cm
Nominal thickness	1.1 mm	0.7 mm
Surfaces roughness	~1 nm/10s μm	<~0.5 nm/10s μm
Surface flatness	>~100 nm/10s mm	<~30 nm/10s mm
Thickness variation	<~30 μm/4 ft^2	<~15 μm/~100 ft^2
Substrate warp	~1 mm/4 ft^2	<~0.3 mm/~100 ft^2

Substrate roughness, the smallest scale surface deviation of the substrate of interest in the AMLCD application, can be propagated into the interfaces of the TFT structure, thereby impacting backplane device function on the scale of the TFT itself [14].

Surface flatness, caused by deviations of the substrate thickness on the scale of tens of millimeters, is particularly critical in controlling the spacing of the two substrates in the AMLCD cell, commonly known as cell gap. Cell gap deviation less than 100 nm can cause visible contrast deviations, especially in advanced liquid crystal modes such as IPS and MVA.

Thickness variation on the scale of the entire substrate area is of importance in meeting depth of focus requirements for lithography. Also, the replacement of spin coating for photo resist and other organic resins employed in the AMLCD process with direct dispensing requires exceptional flatness.

Finally, substrate warp is a permanent curvature of the substrate, which can range from a simple bow in a single direction or a more complex shape. A substrate with excessive warp can result in handling errors. Both absolute value of warp and its geometric nature are salient factors in defining the warp requirement. For example, a common handling error is the inability of the substrate to be pulled flat upon the vacuum stage of a photolithographic stepper. Simple cylindrical warp of a given level is less likely to result in a vacuum error than dome shape or more complex warp.

Surface Quality

During the early development of the AMLCD process, substrate surface was a significant source of yield loss due to mechanical damage (scratches) or contamination (particles or foreign residue). Substrate surface quality has been a focus of continuous improvement in substrate manufacture for over two decades. Substrate quality is characteristically specified by inspection criteria: originally by manual inspection under bright illumination and comparison to limit samples, today by a variety of substrate manufacturer specific and proprietary automated optical detection devices that have extended detection limits and reliability well beyond that of the human eye. However, glass is still typically specified in supplier literature by manual inspection criteria [15].

Particulate contamination is a matter of continuing focus in the AMLCD industry. Typically this attribute is quantified in terms of a maximum permissible size and a maximum density of particles below that size. The actual particle specification is generally determined empirically through collaboration between the AMLCD manufacturer and the substrate supplier. That specification is dependent upon the specific customer process, the method used for particle detection, and the intended application. Typically, the maximum permissible particle of today's AMLCD substrate is equal to or less than 5 μm in diameter, and particle densities are measured and specified down to the 1 μm scale. For some applications, such as polysilicon, the monitored minimum particle size may approach 0.5 μm.

4.1.3 Advanced Physical Attributes

As the AMLCD substrate industry has adopted larger substrate sizes and display applications have required more precise device design, new substrate performance attributes have emerged that are determined by glass compositional and manufacturing process variables.

Stress in the glass, defined as a load per unit area (psi), is set during the forming process and is created by thermal and mechanical conditions. *Distortion* is in plane deformation of

a substrate as a result of stress release upon cutting the glass. An increased thermal expansion coefficient can exacerbate warp and in plane dimensional distortion to the substrate when the substrate is exposed to a thermal gradient during the manufacturing process. These distortions cause feature misalignment (in the TFT plane or between the TFT and color filter plates) or handling problems.

Glass distortion is one of several components that impact the TFT/color filter (CF) alignment quality. In order to build an acceptable panel, the display manufacturer can only tolerate a certain level of misalignment between the TFT and CF plates. Light leakage will occur if the TFT/CF plates are not aligned correctly. Distortion is defined differently by each customer; however, specifications are typically between 2 and 4 mm.

Stress is the internal parameter used in manufacturing to monitor and control the forming process, and is used to accept or reject glass. Stress can be related to the forming process and helps control product quality. Also, measurements can be done frequently. In contrast, distortion measurements are time consuming, difficult, and product specific (e.g., cut pattern).

Optical retardation, the effect of two rays of light traveling at different velocities through a material, can cause unintended polarization anomalies in an LCD panel. These can be induced from panel design, manufacturing, and operation, which have become a larger concern as panel performance continues to advance [16]. ➲ *Figure 2* illustrates the results of a finite element model, a numerical simulation of the impact of optical retardation on a hypothetical panel's viewing performance to illustrate how glass composition impacts panel performance. The conditions illustrated are for matched glass composition panels of, respectively, commercial AMLCD substrate with low thermal expansion (3 ppm/K) and high thermal expansion (9 ppm/K) soda lime glass. The two glass substrates in each panel are assumed fixed at their edges and held stationary in a rigid frame. The TFT plate, closer to the backlight, experiences a higher temperature than the front plate, with a stress producing temperature gradient of 10°C, back to front. Stress birefringence caused by the relative thermal expansions of the two compositions, along with their respective stress optic coefficients a measure, higher for soda lime glasses, of how much birefringence is caused in a material from a stress produces a 5× greater retardation in the soda lime panel.

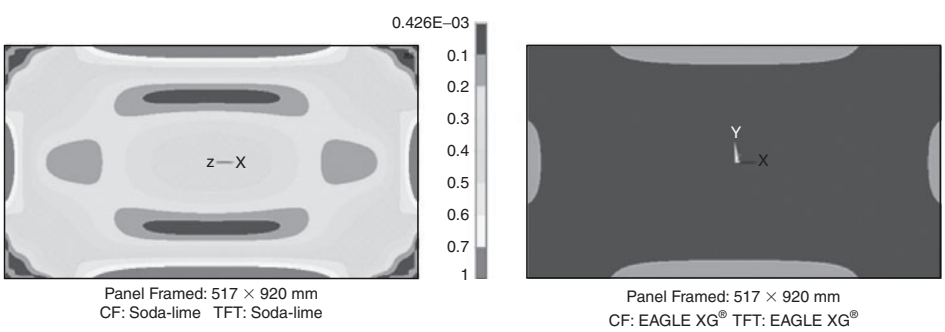

Fig. 2

FEA numerical simulation of the optical retardation in 40-in. diagonal panels. The simulated soda-lime glass display panel on the left shows significant retardation in the center of the panel 3 × the EAGLE XG® panel on the right and 5× the retardation at the panel edges thereby producing a panel with poor contrast (Courtesy of Corning Inc.)

Brighter areas on the display screen indicate increased light leakage through the panel's polarizing films, causing unacceptable contrast irregularities on the LCD screen. These irregularities are more apparent with large size panels.

4.1.4 Substrate Manufacturing Technologies

Because of the importance of the substrate manufacturing method to delivering critical substrate characteristics including flatness and internal stress, a brief discussion of manufacturing technologies used for production of AMLCD substrate glass is presented below.

There are two methods employed to manufacture AMLCD substrates: fusion forming or float plus polishing. In either case, the two process attributes that are critical to substrate quality are glass homogeneity and thermal environment in the forming and transition range of the glass sheet. Glass homogeneity directly impacts flatness and optical uniformity of the substrate. The thermal environment of the glass during the forming process impacts longer scale substrate flatness (warp) as well as shrinkage and stress.

Fusion forming: The fusion process begins when raw materials are blended into a glass composition, which is melted and conditioned in an optical style melter to be homogeneous and virtually defect free. The molten glass is fed into a refractory trough called an "isopipe," filling it until the glass flows evenly over both sides. The two streams of glass rejoin, or fuse, at the bottom of the isopipe, and the fused streams are pulled down by the edges of the sheet to form a continuous sheet of flat, thin glass. The fusion process is sometimes referred to as the downdraw process. Because the glass surface is formed in air, surface tension assures a microscopic smoothness of the fusion surface. No further surface preparation is needed to enable semiconductor like high yield thin film processes of LCD manufacture. The vertical nature of the process means there is a relatively short distance available for controlled cooling of the glass, so substrates manufactured by the fusion process experience a comparatively high thermal gradient, and the thermal conditions are carefully engineered to assure thermal and mechanical attributes meet AMLCD requirements.

Float: The float process also draws molten glass into a thin and flat substrate, but in a horizontal orientation supported by a bath of molten tin. One drawback to this method is that the physics of the float process creates issues in delivering the level of surface flatness required for LCDs. Float glass typically exhibits a characteristic waviness (known as microcorrugation) on the order of tenths of microns over the millimeter scale. To correct this waviness and deliver the nominal flatness requirement, post processing polishing is necessary, scaled with the evolution of the substrate size. On the other hand, float, as a horizontal process, accommodates a longer annealing section and slow cooling of the glass. Cooling in the horizontal direction employs gravity to assure longer scale flatness while extended annealing enhances thermal stability.

Both fusion downdraw and float+polish substrates are used in today's AMLCDs. Customers' choice among glass suppliers (and therefore, the substrate manufacturing process) is a matter of a variety of factors, including application and process specifics. Regardless of whether it originates from downdraw or float, modern AMLCD substrate technology has diverged from that of the conventional commodity glass factory in terms of both quality and scale. Twenty years of collaboration between AMLCD substrate suppliers and the display industry have created a highly optimized platform with control of quality attributes that is well beyond that of commodity glass. A notable aspect of the progress in AMLCD substrate

glass technology has been in the reduction of inclusions, that is, inhomogeneities in the glass consisting of crystalline impurities or trapped air bubbles (known as seeds or blisters). Inclusions, if large enough and close to the substrate surface, can cause a minute protrusion on the surface that can affect the AMLCD cell gap. The density of inclusions in LCD glass, because it is associated with a critical visual defect and yield loss mechanism, has been the subject of continuous improvement in the substrate industry. The glass inclusion quality today is orders of magnitude lower than that of conventional glass.

4.1.5 A Brief History of AMLCD Glass

The first glass used on a commercial scale in AMLCD development was Corning code 7059, first offered to the LCD industry in 1.1 mm thickness (➲ *Table 2*). While the origin of the invention of code 7059 is lost in the historical record, references can be found in Corning Glass Works notebooks as early as 1954. Fusion manufactured code 7059 was first introduced to AMLCD development in 1984. Code 7059 was a simple composition with advantages in high temperature durability and relatively low CTE. Nevertheless, this composition had its limita tions, which were exacerbated as the display industry sought to increase yield and make the LCD platform practical for high volume manufacture. In those early days, manufacturers were using a harsh wet chemistry during substrate cleaning and in photolithography, and the simple barium boroaluminosilicate composition of Corning code 7059 lacked the chemical durability required for this aggressive chemistry. Also, although CTE had been lowered to $46 \times 10^{-7}/°C$ for high throughput thermal processes and driver chip integration, concerns about expansion would only worsen as Gen sizes increased. Therefore, higher thermal and dimensional stability were critical.

The next step was Corning 1737, introduced in the latter half of 1994 [17]. Though the primary target attributes of this composition were increased chemical and thermal durability with reduced thermal expansion compared to code 7059, this glass featured an attribute AMLCD manufacturers had not specifically requested: low density. Achieved by engineering the composition to lower levels of heavy, dense constituents, the low density of Corning 1737

Table 2
Glass property comparison of AMLCD substrates to commodity-type glass compositions

Property	Pyrex®	Soda-lime float	Corning 7059	Corning 1737	EAGLE2000®	EAGLE XG®
Year of LCD commercialization			1984	1994	2000	2007
Anneal point °C	550	550	640	730		720
Strain point °C	505	500	590	670		670
Density °C	2.2	2.5	2.8	2.6	2.4	2.4
CTE ppm/K	3.3	8.7	4.6	3.8	3.2	3.2
Softening point °C	820	730	840	975		970
Alkali content, weight % Na2O	4	4 12	0.1	≤0.05	≤0.05	≤0.05

reduced substrate glass weight in notebook computers (then the primary application), and also greatly facilitated larger substrate sizes, as the reduced weight eased automated handling. By the time of code 1737's introduction, 0.7 mm was becoming the dominant substrate thickness, and low density eased this trend. Another unanticipated benefit of the glass was associated with the robustness of the interface between the glass surface and the TFT. Customers in the Gen 2 development were depositing highly stressed refractory metal films to reduce the electrical resistance of gate lines for larger notebook panels, and the intrinsic high glass lattice strength of Corning 1737 created a more reliable interface for these films.

In the late 1990s, Corning began a structured collaboration with panel manufacturers to develop EAGLE$^{2000®}$. The development targets for EAGLE^{2000} were to continue the optimization of key glass properties: density was reduced to 2.4 g/cm^3 and thermal expansion to 3.2 ppm/K. Of course, no one yet envisioned the 3 m^2 platform of Gen 10, but clearly the industry did articulate a need for very large substrates capable of high throughput processing. By design, EAGLE^{2000} had enough headroom in its basic specifications to meet the scaling of AMLCD well beyond display industry expectations.

Today's state of the art glass substrates for LCDs are highly engineered, high value, specialized glass compositions, such as EAGLE XG®, an extension of the EAGLE family into an environmentally friendly glass substrate that contains no added heavy metals or halides.

4.1.6 Movement to Larger Substrates

Arguably, amorphous silicon TFT LCD has won the display platform battle based on its scalability and versatility, which in part have been enabled by the ability of aluminosilicate substrate manufacturing technologies to produce increasingly larger generation size substrates while maintaining thin capability (0.5 0.7 mm) [18].

The key advantage of the increase to larger Gen sizes is that they provide the panel maker with greater economies of scale due to the ability to fabricate multiple panels on a substrate as well as to produce larger panels. The increase of substrate size by the Gen 1 to Gen 5 progression was primarily motivated by information technology applications (notebook and desktop monitor). The LCD TV era began with Gen 6, which offered good substrate utilization for the manufacture of 32″ (8 up) and 37″ (6 up) panels. Gen 7 and Gen 8 were deployed for the 46″ and 52″ class LCD TV. *Table 3* and *Fig. 3*, respectively, tabulate and illustrate the increase of substrate size in the LCD era as a function of time and application.

Today's state of the art Gen 10 platform is unique in that it efficiently produces a wide range of panel sizes, including 32″, 42″, and 65″. *Figure 4* shows a simulated Gen 10 substrate with these sizes illustrated. Note that the substrate thickness is only 0.7 mm. Because the glass is so large and so thin, the substrates are handled exclusively by robots during substrate and panel manufacture.

Sizes beyond Gen 10 may be introduced if panel makers require them, but at present 3 m^2 seems to fulfill the needs for large screens; the need for a platform capability beyond the 60 in. range is unclear.

4.1.7 Trend to Thin

The benefits of using as thin a substrate as practical in LCD has been evident since the early days of LCD, primarily to eliminate weight and thickness in the notebook computer application.

Table 3
Approximate AMLCD substrate sizes listed by generation. Since the actual size deployed differed between panel manufacturers, typical or representative dimensions have been chosen for the generation

Generation	Size (L × W, cm)	Date introduced
1	30 × 40	1990
2	37 × 47	1993
3	55 × 65	1995
3.5	60 × 72	
4	68 × 88	2000
4.5	73 × 92	
5	110 × 130	2002
5.5	130 × 150	
6	150 × 180	2003
7	187 × 220	2004
7.5	195 × 225	2005
8	220 × 250	2006
10	288 × 313	2009

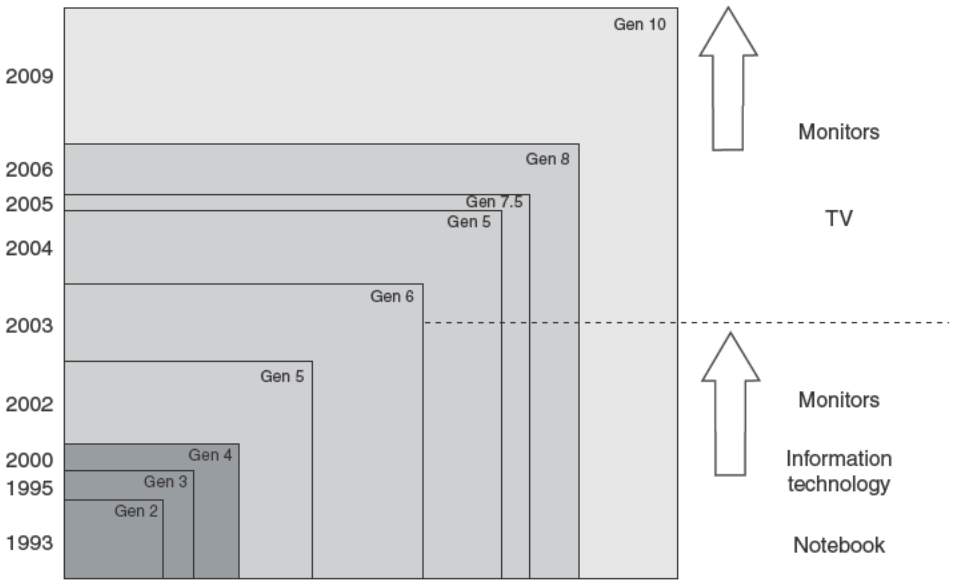

Fig. 3
Evolution of substrate sizes (Courtesy of Corning Inc.)

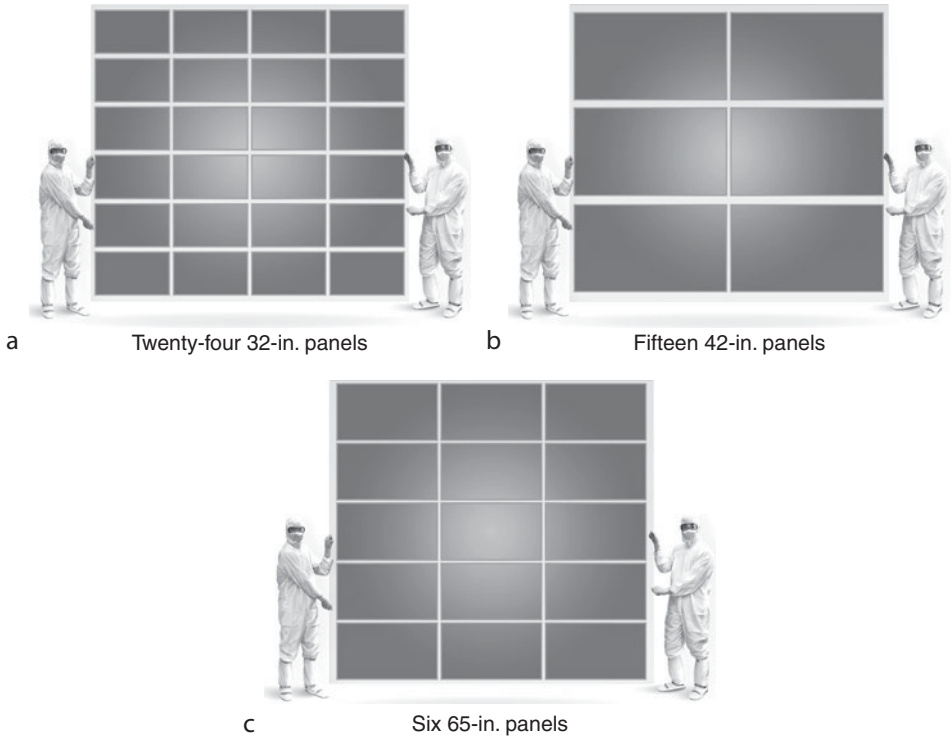

Fig. 4
Simulated Gen 10 substrate illustrating to scale the high utilization of the manufacture of popular 16:9 format LCD-TVs (Courtesy of Corning Inc.)

The use of thinner glass also brought some process advantages such as faster heating ramps for thermal process. Today, design is a contributing criterion for the use of thin glass as the thinnest possible panel is a source for product differentiation in both portable and stationary applications.

The fusion process among other sheet manufacturing processes has demonstrated the potential for making very thin glass, even to 0.1 mm and below. However, thin glass capability at the substrate manufacturer has outpaced the ability of AMLCD manufacturers to employ thin glass in their process. The primary challenges have been glass handling and breakage in TFT and color filter process automation. In the early 1990s, most AMLCD processes were designed around the 1.1 mm standard. By the advent of Gen 3 in 1995, 0.7 mm had almost entirely become the standard through mechanical engineering innovations in the AMLCD process equipment. Today 0.5 mm is a commonly used substrate thickness for most portable device panels manufactured on Gen 4 and Gen 5 lines, while even larger Gen sizes may have installed capability for thin glass in order to have "flexible manufacture"; that is, the capability to produce both portable and larger stationary panels on the same line.

Currently, many portable panel manufacturers employ an acid thinning process on finished displays to create the thinnest possible panel while avoiding the difficulties in handling thin glass in their front end processes. This approach has worked well for the manufacture of low volumes of panels, but concerns with the impact upon strength and the added cost of this

process have motivated investment into 0.3 0.4 mm handling as thin devices have become mainstream and destined for premium devices.

It is likely that even thinner glass will be targeted for display substrates or other components. The advent of touch capability into many display devices has also stimulated increased emphasis on thin glass as device designers do not want to increase panel thickness with the additional pieces of glass required for touch sensor and a cover glass. It is not unreasonable to expect that glass as thin as 0.2 mm may be required for touch components and perhaps even within the panel. At this point, the glass is thin enough to allow it to be conformable or even flexible if suitably packaged in the device.

At 0.1 mm thickness and below, the possibility of truly flexible glass delivered to the panel manufacturer on a spool for roll to roll manufacture of displays can be discussed. e Paper seems to be a target for this approach given the interest in ultra low cost printing processes for e Paper applications and the emphasis on true flexibility of the display. At the present time, glass manufacturers have demonstrated spooled glass and it appears that its commercialization is primarily a matter of solving difficult but tractable mechanical engineering problems. However, roll to roll processing for display manufacture is still in early research and development. *Figure 5* summarizes the status of thin glass capability as a function of substrate size and intended application.

4.1.8 Environmental Trends

Increasingly, new technologies and products are evaluated through the lens of their environmental impact across the entire life cycle, including materials manufacturing, product

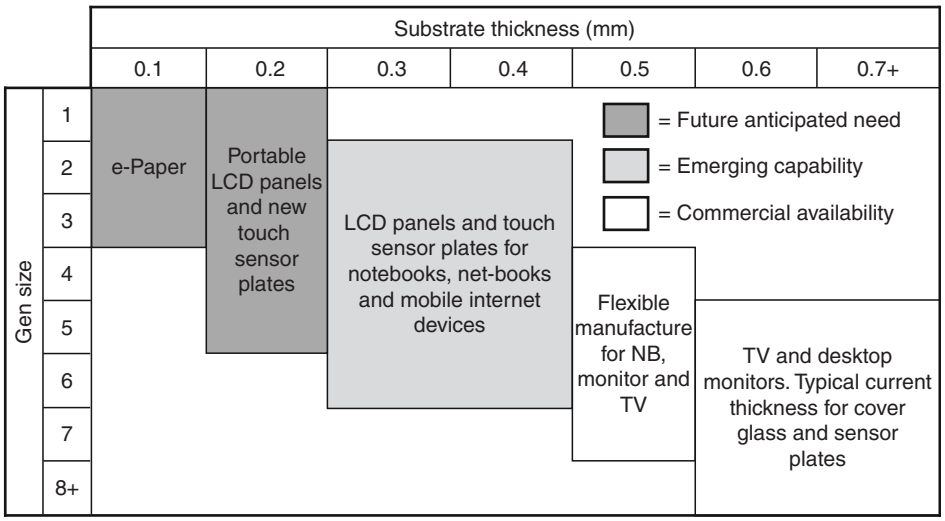

Fig. 5
Substrate thickness as a function of Gen size: current commercial availability, emerging capability (limited commercial availability or in development), future anticipated need requiring substantial platform innovation (Courtesy of Corning Inc.)

fabrication, device use, and end of life. While AMLCDs are a substantial improvement over the CRT in this regard, the life cycle trend still poses a challenge for the LCD manufacturer, since there are technical barriers to removing all materials of environmental concern from the display. This also includes the glass composition and its manufacturing process.

One of the main quality requirements for LCD substrates has been that they must be completely free of even microscopic bubbles. Eliminating them has traditionally meant using "fining" agents such as arsenic and antimony to prevent bubbles from forming. But the use of these heavy metals can result in potentially harmful byproducts in panel manufacturing. Removing them was the challenge in a "green" LCD substrate.

The elimination of heavy metals from the glass composition was seen as necessary in the long term because of emerging environmental regulations worldwide. While in the glass, these heavy metals constitute no hazard to the user. However, concerns arise about what happens when the display reaches the end of its useful life. Impending environmental regulations require manufacturers to establish plans for recycling electronic products and their components.

For electronics manufacturers, then, there are two choices: recycle the glass from discarded equipment, or use a glass that does not contain heavy metals in the first place.

In CRT technology, heavy metals such as lead are used in the glass composition to protect the viewer from X rays. The CRT industry's approach to the environmental challenge has been to recycle televisions at the end of their life and reuse the glass. Because of the sheer amount of glass in a CRT television (over 25 kg glass in a 32″ television), the simplicity of disassembling a CRT and the less demanding quality requirements of CRT, this approach made economic sense.

Yet the CRT approach of recycling glass is not adaptable to LCD, for several reasons. First, LCD televisions contain less glass than CRTs, so there is less benefit to recycling. Second, recycling is much more difficult due to the complex construction of the LCD device itself. Finally, whereas the quality of CRT glass does not affect the viewing experience, LCD glass has demanding quality requirements, which call for a pristine glass. For all of these reasons, it is impractical to recycle LCD glass back into substrate manufacture. The only logical solution for minimizing the environmental impact of LCD glass was to eliminate heavy metals up front.

In 2006, Corning commercialized the industry's first composition to contain no added heavy metals or halides: EAGLE XG®. In addition to removing arsenic, antimony, and barium from the glass melting process, EAGLE XG also eliminates the use of halides, such as chlorine, fluorine, and bromine, which can create corrosive acid byproducts during glass manufacturing. The adoption of this glass and similar green glass compositions from other AMLCD substrate manufacturers that have eliminated heavy metal content has been rapid.

4.2 Polysilicon (p-Si) and OLED

Over the last few years, p Si has clearly differentiated itself from a Si in various applications, especially where display manufacturers needed fine quality visual performance in a compact form factor with optimum power efficiency. Polysilicon semiconductor performance is superior to that of a Si in certain uses, allowing manufacturers to place more complex circuitry on the glass during fabrication of the display array. These functions include much of the display driver circuitry, which would otherwise require off panel discrete chips with complex packaging and interconnection.

Compared to the a Si process, the low temperature polysilicon (LTPS) process is much more demanding in terms of temperature, surface, and dimensional requirements. The LTPS process requires the glass to be stable, without changing its shape or dimensions at 600°C and higher.

Previously, p Si manufacturers had to heat treat a Si glass to stabilize it to high temperature in what is effectively a pre shrinkage process. This pre treatment makes the entire process more complex, and it creates the potential for the glass to change shape under high temperature through thermal sag. The extra handling can also degrade the surface quality of the glass, possibly requiring (for some substrate manufacturers) special polishing to ensure the extraordinary surface quality that the polysilicon backplane demands.

In OLEDs, the limitations of p Si backplane processes have comprised a substantial technical challenge that has slowed the growth of the OLED platform by limiting its adoption to small displays. Because OLEDs are current driven devices, they require a backplane with much better performance than a conventional AMLCD. Laser annealing technology used for crystallization of the silicon layer in p Si AMLCD meets OLED backplane current requirements but is not economical or technically feasible for scaling to large size that would be required for OLEDs to enter the TV market. One possibility of a scalable OLED backplane technology is microcrystalline silicon technology, which, although not yet commercialized, may incorporate high temperature processes such as solid phase crystallization and rapid thermal annealing in the 600 700°C range [19 21], which are beyond the capabilities of a thermally stabilized conventional a Si substrate.

4.2.1 High-Temperature Substrates for p-Si and OLED Backplanes

As an alternative to a stabilized a Si glass, glasses with an intrinsic stability at high temperatures are accessible in the aluminosilicate glass family [22]. One such composition, Jade®, a fusion formed glass, requires no secondary heat treatment or polishing to meet the surface and thermal stability requirements of the LTPS and OLED processes [23]. The high intrinsic viscosity of Jade substrates enhances thermal durability, providing a potentially wider process window for TFT fabrication.

A decrease in thermal sag at elevated temperatures reduces losses due to handling and vacuum chucking errors. ➲ *Figure 6* contrasts the relative (accelerated) deformation of the Jade substrate and an a Si substrate at elevated temperature.

The aforementioned option for eximer laser crystallization p Si process, microcrystalline silicon process, features a solid phase crystallization step at temperatures above 600°C. ➲ *Figure 7* illustrates compaction performance of Jade in this thermal regime compared to that of a conventional a Si glass.

4.3 High-Strength Glass Used in AMLCD Panels

Although not necessarily a contributor to the functionality of the display, high strength glass is increasingly incorporated in AMLCD panels. Many portable devices, especially handsets, require a protective cover for shock and abrasion. As previously mentioned, the addition of touch functionality has added thin glass to the device while increasing the need for mechanical protection. Finally, design esthetics is stimulating the employment of high strength glass

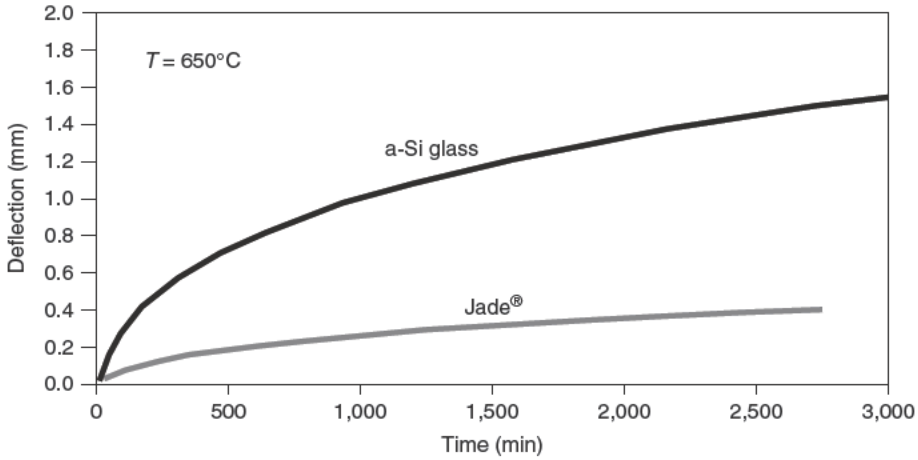

Fig. 6
Elastic deformation of Jade glass compared to conventional a-Si glass (EAGLE XG®) at 650°C (Courtesy of Corning Inc.)

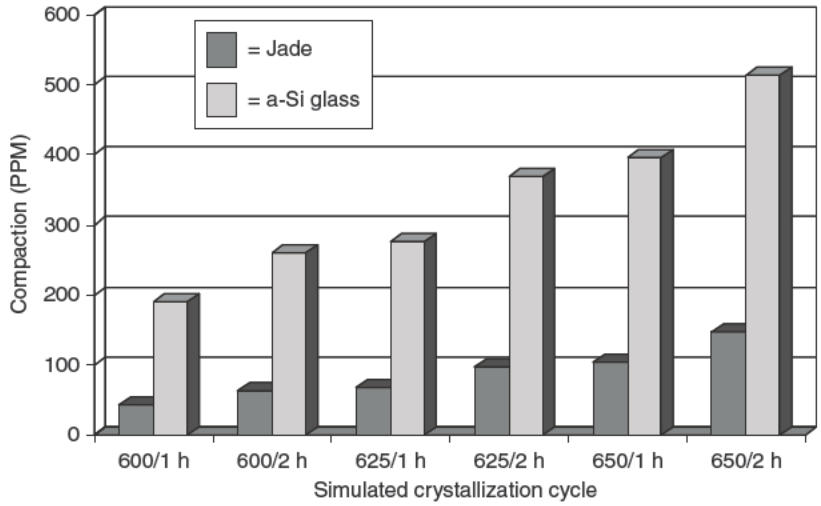

Fig. 7
Compaction of Jade compared to a-Si glass (EAGLE XG®) in the solid phase crystallization thermal range (Courtesy of Corning Inc.)

as a cover in so called borderless design, that is, with no protective bezel surrounding the display panel.

Portable devices from cell phones to notebook computers require more durability against mechanical shock, stress, and abrasion than stationary display centric devices. In order to protect the display panel, manufacturers have employed a cover of tempered soda lime glass or

scratch resistant polymer, which is counter the trend toward minimal device thickness. Increasingly, thin chemically tempered glass is being used as a protective cover.

Corning® Gorilla Glass is one example of a new class of materials used in AMLCD and OLED displays that have been engineered for optimum mechanical performance in cover glass applications [24]. Glass strength can be enhanced through a chemical tempering process that exchanges small mobile alkali ions for larger ones in a high temperature salt bath, inducing a compressive layer on the glass surface. This compressive layer increases the amount of force required to either scratch the surface or cause failure by exerting tensile force. The Gorilla Glass composition is also of the aluminosilicate family; however, unlike aluminosilicate AMLCD substrates, it contains alkali constituents of sodium and potassium to allow ion exchange. While any glass containing sodium can be strengthened by chemical tempering, the alumino silicate glass structure optimizes the effect.

Table 4 is a summary of key properties of Gorilla Glass compared to other cover materials commonly used in AMLCD. Ultimately, the functional strength of a device will be determined not by the design strength of its components in their pristine state, but by the ability of the various components to maintain that strength after use in the intended application. This is how employing chemically tempered aluminosilicate glass as a cover material brings value to strong and thin portable devices. *Figure 8* shows that the reduction of strength of Gorilla Glass is far less than that of chemically tempered soda lime glass after abrasion damage.

The difference in retention of strength in use is due, in part, to the greater depth of the strengthening compressive layer in Gorilla Glass compared to that of soda lime. The Gorilla

Table 4

Corning Gorilla Glass properties compared to two other commonly used AMLCD cover materials, PMMA (polymer) and ion-exchanged soda-lime glass

	PMMA	Ion-exchanged soda lime	Ion-exchanged Gorilla® Glass
Process	Extrusion, injection	Float, slot draw	Fusion
Tg (Range) (°C)	~105°C	514 546°C	553 602°C
Strain point (°C)	NA	514°C	553°C
CTE × 10^{-6}/°C (0 300°C)	700 900	80 90	91
Thickness availability (mm)	>0.70	>0.55	>0.55
Density (g/cm^3)	1.17	2.4 2.5	2.45
Young's modulus (GPa)	1.8 3.1	72	73.3
Refractive index	1.48 1.50	1.52	1.51
Light transmission (400 700 nm)	>88%	>90%	>91%
Compressive stress (MPa)	NA	400 600	650 825
Depth of layer(μm)	NA	10 30	40 80
Pencil hardness	3 4H (coated)	6 8H	9H

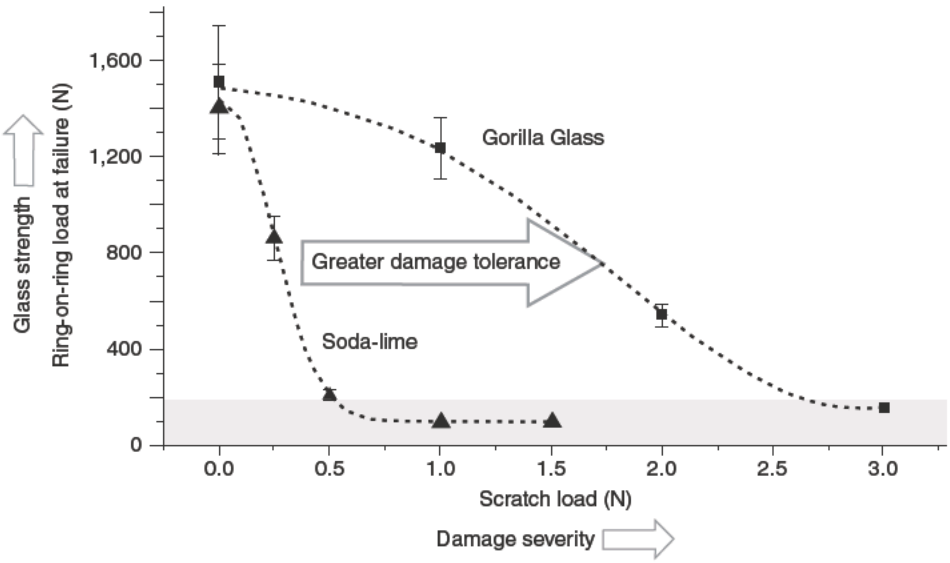

Fig. 8
Strength reduction of Gorilla Glass and chemically tempered soda-lime glass after abrasion (Courtesy of Corning Inc.)

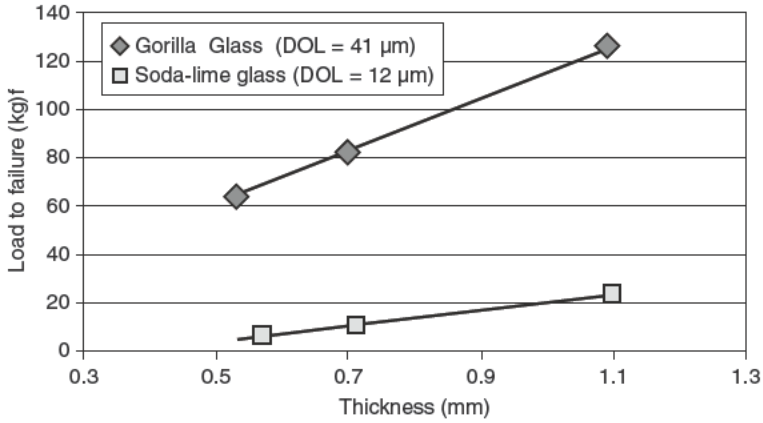

Fig. 9
Ring-on-ring strength of various thicknesses of Gorilla Glass and soda-lime glass after abrasion (Courtesy of Corning Inc.)

Glass composition was developed to maximize the depth of layer (DOL) in the compressive strengthening effect a key factor in making Gorilla Glass a contributor in the drive to thin form factor [25]. *Figure 9* illustrates the fact that Gorilla Glass with a deeper DOL results in much higher retained strength after abrasion in reduced thickness.

5 Summary and Future Directions

The modern AMLCD and OLED platforms have benefited from decades of collaboration between display manufacturers and glassmakers, resulting in highly optimized aluminosilicate glass substrates. These substrate requirements including glass composition, surface quality, advanced physical attributes, and other factors strongly depend upon the specifics of the application and the processes used to manufacture the panel.

From its origins in small panels to the high volume notebook computer, computer monitor, and large screen TV panels of today, the success of the AMLCD platform has been facilitated by the scalability of a Si substrate manufacture. In high performance portable devices as well as the emerging OLED platform, increased thermal durability attributes has driven substrate design. Increasingly, glass is also employed as a structural element of the display device, as evidenced by a cover glass that facilitates the incorporation of touch functionality and offers design flexibility. The aluminosilicate glass system has provided options for chemically tempered cover glass and touch panel components that provide enhanced glass strength and device reliability in thin form factors.

It is unlikely that the trend of progressively larger size substrates will be sustained much beyond the 3 m dimension (the present Gen 10), due to the diminishing pull for size capability beyond a 70″ diagonal screen within the TV application and the diminishing benefits for the economies of scale offered by larger size substrates. In established applications, the focus of display substrate innovation will be in reducing system cost and in enhancing the immersiveness of the flat panel display experience. This is best accomplished, in the author's opinion, by systematically and collaboratively enhancing existing substrate attributes that have already been under continuous improvement throughout the LCD era. For example, scalable OLED TV technology will involve further enhancements to the thermal durability aspects of aluminosilicate substrates a process that has been underway since the emergence of LTPS in the 1990s.

The next step change in creating an immersive flat panel visual experience is achieving a compelling 3 D effect for LCD TV. This involves controlling left and right eye information via polarization modulation, by either use of light shutter eyeglasses or by interposing an active retarder between the display and viewer (see Sect. 9, 3 D Displays). The substrate or display cover glass can induce nonuniform optical retardation (discussed above in Sect. 4.1.3), with the potential of creating anomalies in the 3 D effect, including chromatic distortions and cross talk between left and right eye information. Likewise, the 3 D effect is enhanced by reducing the glass thickness in the display stack [26]. Therefore, optimizing the substrate for 3 D involves further improvements in attributes (thinness and retardation) that have already been present as central substrate themes in the evolution of the AMLCD platform.

Looking ahead, new display applications are creating pull for new categories of glass attributes. For better or worse, an undeniable trend is that our environment will increasingly be saturated with timely, interactive, and compelling generated visual information displayed on an increasing diversity of electronic devices. e Paper is seen as one of the key emerging platforms. As a material, glass brings a unique combination of transparency, dimensional stability, strength, and a surface that can be both chemically and physically compatible with semiconductor function. With continued innovation, the glass substrate will continue to serve the display industry as an enabling component capability within emerging platforms. Gaps, however, do exist primarily in the convergence of glass capability, display process technology, and device architecture for new display applications.

As we progress to an era of ubiquitous display, flexibility is a targeted dimension of high performance display function that has been only partially fulfilled (see Part 5.6, Flexible Displays). When properly packaged and handled, thin glass can be a flexible and strong display substrate; however display manufacturers have not yet made the necessary investments to employ thin flexible glass; nor have glass compositions been optimized for flexibility. Likewise, ubiquitous display will require much lower manufacturing costs than the current sheet based process, and it is clear that roll to roll processing offers a path forward. As discussed above, glass as a R2R or flexible display component substrate for low cost manufacture is feasible, but its development will require close collaboration between the device designer, the display manufacturing equipment industry, and the advanced glass substrate manufacturer. This collaboration will be a central theme as electronic display evolves to achieve ubiquity.

6 Further Reading

There has been no comprehensive review of display substrate technology since the early days of the AMLCD platform. Although dated, previously published collaborations of the author [4, 27] provide some details of glass properties and their impact upon LCD product and process performance. More recently, a broad discussion [16] of the dynamics behind the sustained value of highly engineered substrate glasses in an era of increased display panel commodization may have interest for the general reader. Very recently, Ellison and Cornejo (two principals in display substrate composition innovations at Corning Incorporated) have presented an insightful and entertaining retrospective on the LCD substrate era that delves deeply into glass composition design for LCD product and process [28].

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