Flexible glass substrates for roll-to-roll manufacturing

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Abstract

Substrate choice is critical for the overall optimization of flexible electronic device design, fabrication process, and performance. Glass substrates offer advantages compared to alternatives including dimensional and thermal stability, hermeticity, transparency, and surface quality. Adding to these benefits, ultra-slim flexible glass, ≤200μm thick, enables the use of glass in roll-to-roll (R2R) equipment and fabrication of ultra-thin and light weight devices. This paper discusses the benefits of flexible glass in electronic applications as well as its use in R2R fabrication processes. A description is included of proven methods for maintaining the mechanical reliability of flexible glass in R2R methods.

Introduction

Recently there has been an increasing interest in flexible electronics such as displays, touch sensors, and photovoltaics. These applications, in general, value high-performance, light weight, ultra-thin, and conformal devices. The capabilities and advantages of web processing offer the ability to fabricate high-quality devices with high throughput manufacturing methods. Specifically, advances in R2R printing, vacuum deposition, and patterning methods enable a next generation of high-resolution, high-performance electronics.

The device substrate is an integral component in the overall optimization of flexible electronics. It affects the final form factor of the device as well as performance and is also critical in determining process parameters and manufacturing yield. The substrate is a significant element in all aspects of the device (design, manufacturing, and performance).

Flexible Glass Advantages

Ultra-slim flexible glass delivers several advantages for device performance and lifetime. Besides extrinsic properties related to thickness and weight, flexible glass has several intrinsic properties that improve device quality and lifetime. Figure 1, for example, shows the optical transmission of flexible glass compared to representative PEN and polyimide films. The transmission in the visible range is limited by the 4% surface reflection loss, and the transmission cut-off in the UV is due to absorption. No observable scattering or haze is present in the flexible glass substrates.

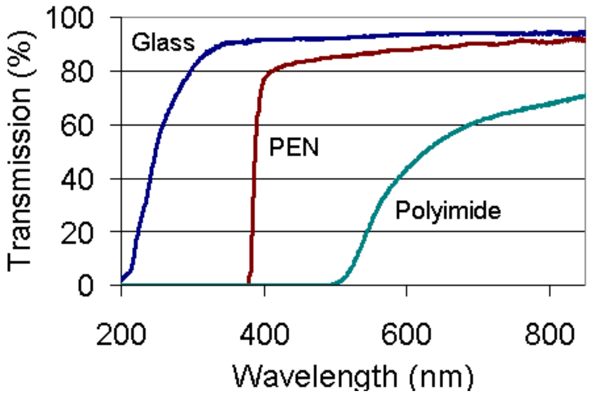

Figure 1: Optical transmission of flexible glass.

Another example, Figure 2, shows the surface roughness as measured by AFM of flexible glass compared to polymer films. “A” and “B” for each sample set refer to the substrate front and backside surfaces. As shown, flexible glass has significantly lower Ra and Rpv roughness values. This translates into higher performance thin-film devices. These intrinsic flexible glass properties, along with the inherent oxygen and moisture barrier properties, enable higher-quality devices. Recently reported devices demonstrate the capability of flexible glass in ultra-thin color liquid crystal,[1] electrophoretic,[2] cholesteric liquid crystal,[3] and electrokinetic[4] display applications.

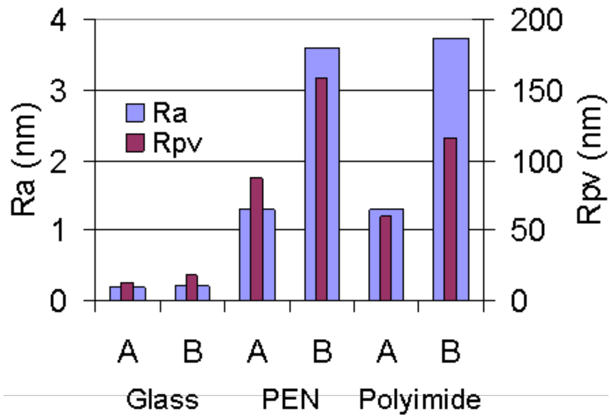

Figure 2: AFM surface roughness of flexible glass.

In addition to improving device design and performance, the intrinsic thermal and dimensional stability of flexible glass enables increased process optimization and manufacturing yield. For example, the ability to vacuum deposit thin films onto flexible glass at elevated temperatures over 300°C enables higher optical and electrical performance as well as increased adhesion. Not only does flexible glass have high thermal capability, but it is dimensionally stable as well. Glass dimensional changes due to thermal expansion are predictable, and mechanical properties are also stable in this range. This is illustrated in Figure 3, where stress-strain measurement results are shown for both 25°C and 150°C. The stability of the flexible glass modulus is compared to the significant reduction in stability for the PEN and polyimide modulus values. The data plotted in Figure 3 was taken using a DMTA with a sample gage length of 10mm.

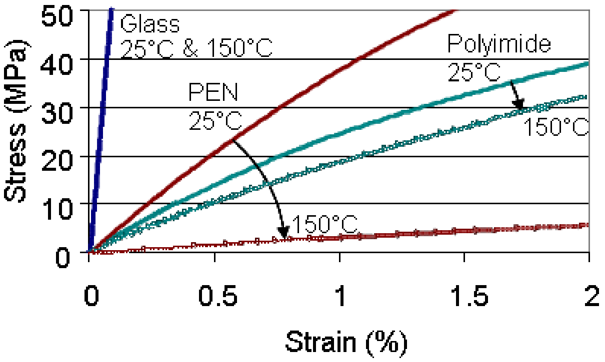

Figure 3: Dimensional stability of flexible glass based on DMTA measurements.

Figure 4 plots stress-strain data taken on R2R equipment designed to test web conveyance. Sample lengths were approximately 1m. The data points were collected by strain gages, and the scatter is due to system variability. The solid lines are predicted results based on documented bulk modulus values. Both the flexible glass and PEN were approximately 100mm in width and 100µm thick. This shows that for a 5MPa stress (5kgf tension), a 100mm length of glass will stretch 7µm, but a PEN web will stretch 42µm. Considering that display pixels are typically in the size range of 20-30µm, flexible glass web has a significant advantage in flexible electronics requiring high resolution and high registration patterning or large area.

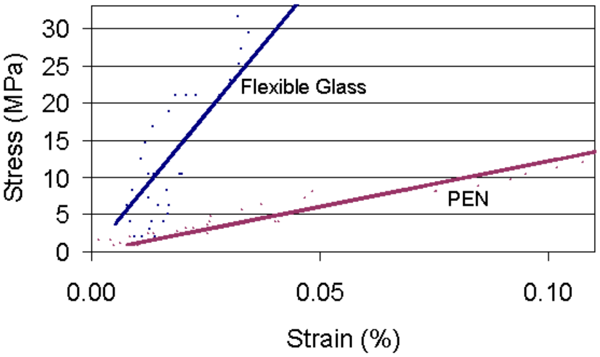

Figure 4: Strain gage dimensional stability measurements of flexible glass in R2R web conveyance equipment.

Ultra-slim flexible glass offers inherent benefits such as dimensional and thermal stability, hermeticity, transparency, and surface quality compared to alternative flexible substrates. These properties enable high-resolution, high-performance devices as well as full optimization of manufacturing processes.

Flexible Glass Web Mechanical Reliability

As mentioned, ultra-slim flexible glass has several advantages compared to alternative substrates for high-quality device design, performance, and fabrication. However, to be practical for R2R manufacturing, manufacturers must achieve mechanical reliability of flexible glass in web processes. In general, reliability of glass is statistical and related to the distribution of stresses and defects.[5] Mechanical failure occurs when the combination of stress and defect size reach a critical combination. This paper focuses specifically on the reliability of flexible glass for web processing and methods to minimize both handling stresses and defects due to contact damage.

To minimize stresses during handling, large flexible glass substrates should be conveyed with roller systems similar to other flexible web materials. Handling large areas of flexible glass with methods designed for rigid sheet substrates will lead to stress concentrations and mechanical failure. Since the moment of inertia and associated stiffness are proportional to $(\text{thickness})^3$, glass substrates become very flexible as their thickness decreases. To put this in perspective, Figure 5 plots the relative stiffness of a representative glass and polymer material with Youngs modulus values of 75GPa and 10GPa, respectively. This shows that a 50μm glass substrate requires the same force to bend as a 100μm polymer film. Similarly, an 80μm glass substrate has a stiffness equivalent to a 150μm thick polymer film. Therefore, flexible glass should be handled in roller conveyance systems appropriately designed for this web material.

In terms of stress associated with roller systems, Figure 6 plots the calculated bend stress of glass as a function of radius for different thicknesses. As shown, a substrate with a thickness of 500μm, typical thickness of rigid LCD substrate applications, experiences a significant bend stress at radii typical of web processing. To reduce bend stress in R2R manufacturing, a glass thickness approaching 100μm or below is targeted.

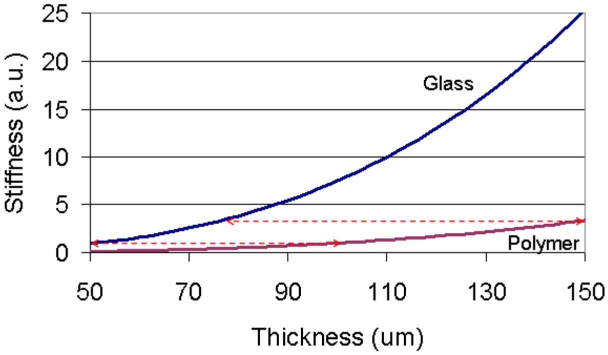

Figure 5: Relative stiffness of flexible glass.

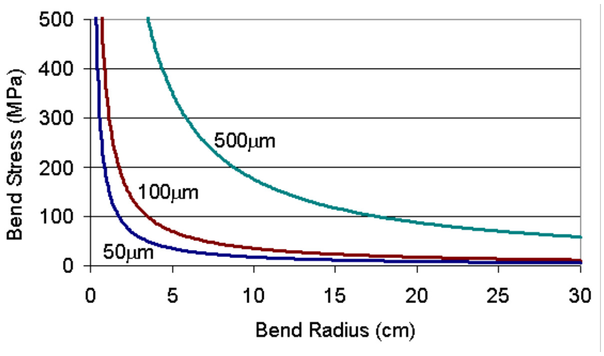

Figure 6: Calculated glass bend stress.

Minimizing defects in the glass caused by contact damage is critical for mechanical reliability. Depending on the defect size and geometry, the failure stress of glass can decrease by >10x as damage occurs. One approach to minimize the probability of damage is to use protective coating materials. As demonstrated by the example of glass optical fiber, high mechanical reliability of glass is obtained when the surfaces are protected from contact damage. Similar to glass fiber, the flexible glass web can be completely encapsulated in a protective material to avoid damage. The protective materials need to be selected based on required process compatibility. This approach, however, requires that any electronic devices actually be fabricated on the protective material instead of directly on the glass. Another approach illustrated in Figure 7 is to use edge tab protective features to prevent damage to the glass. These edge tab features act as a physical spacer when glass is conveyed over a roller or wound onto a spool. When glass is bent around a roller, these edge tabs prevent contact damage from occurring to the glass surface. As Figure 7 shows, the edge tabs also allow a substantial area of the flexible glass surface to be available for electronic device fabrication. Even with the protective edge tabs present, electronic devices can be fabricated on both surfaces of the high quality flexible glass web. This enables utilizing the glass benefits such as low surface roughness and hermeticity to produce high quality electronic devices.

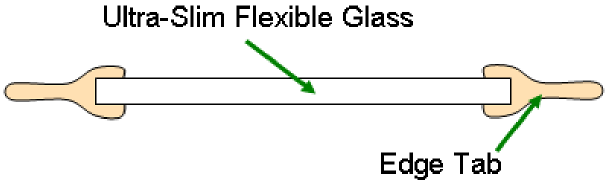

Figure 7: Cross-section of flexible glass web with protective edge tabs.

After fabrication, individual devices built on the flexible glass web can be cut out for final device packaging. Methods such as laser cutting[6] result in high quality edges. As shown in Figure 8, individual device substrates can be cut out of the flexible glass web removing the protective edge tabs before packaging.

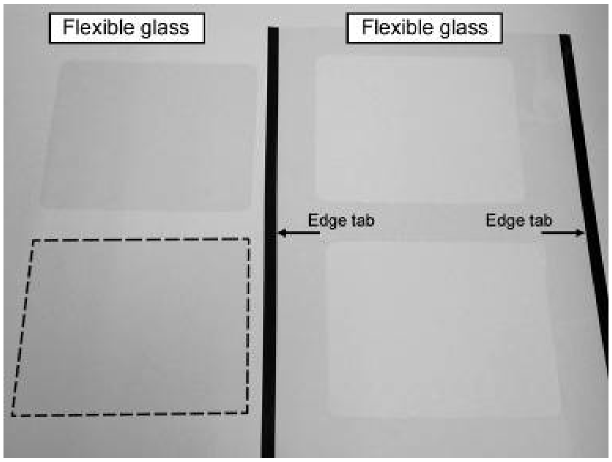

Figure 8: Individual device substrates cut from flexible glass web.

Flexible Glass Web Demonstrations

We performed several demonstrations to evaluate the compatibility of a flexible glass web with edge tabs in R2R processes. We previously reported on the use of flexible glass web in R2R patterning of ITO.[7] This included ITO deposition, photoresist slot die coating, exposure, ITO etch, and photoresist strip. Since then, we have performed additional web conveyance and R2R screen printing evaluations.

As a demonstration of web conveyance, Figure 9 shows a 330mm width flexible glass web with edge tabs propagating through a 150mm diameter roller system. As shown, the web path includes a wrap angle of 180° around a central roller.

Figure 9: Flexible glass web conveyance testing.

We also performed screen printing evaluations to demonstrate compatibility with device processing equipment. This was a step-and-repeat process that included:

- advancing the flexible glass web,
- pulling it flat to a vacuum chuck,
- screen printing Ag ink patterns,
- releasing the stage vacuum, and
- advancing the web to a separate curing station.

Consistent 150μm width features were printed with a height of 14μm ± 1μm. Figure 10 shows flexible glass being conveyed through the R2R screen printing equipment, and Figure 11 shows a single print made on the ultra-slim flexible glass web.

Figure 10: Flexible glass web in R2R screen printer.

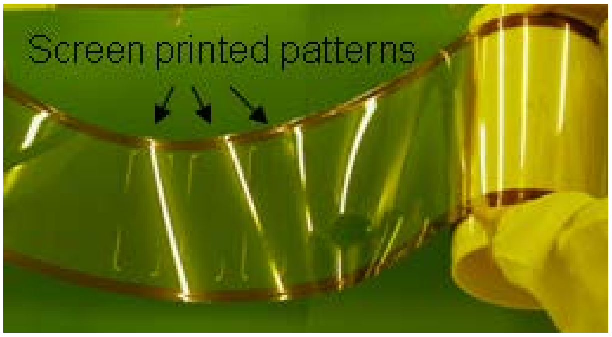

Figure 11: Screen printed Ag ink pattern on flexible glass web with edge tabs.

Conclusion

Ultra-slim flexible glass, ≤200μm thick, offers several advantages for web manufacturing of electronic devices. Benefits of glass include: high quality surface, high optical transmission, thermal and dimensional stability, and hermeticity to oxygen and moisture. Similar to other web materials, flexible glass is appropriately conveyed through fabrication equipment using roller systems. These roller conveyance systems appropriately control the handling stress in the flexible glass. In addition to managing stresses, the use of edge tabs protects the flexible glass from contact damage in R2R equipment. Initial web conveyance and screen printing results demonstrate the compatibility of flexible glass with edge tabs in web processes. Flexible glass enables high-quality electronic devices with its overall benefits for device design, performance, and web processing.

Acknowledgements

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References

[1] Hoehla, S., Garner, S., Hohmann, M., Kuhls, O., Li, X., Schindler, A., Fruehauf, N., “Active matrix color LCDs on ultra-thin glass substrates,” *Electronic Displays Conference*, Nuremberg, March 2-3, 2011.

[2] Lo, P-Y., Liu, C-W., Hsieh, Y-M., Hsu, R., Ding, J-M., Hu, J-P., Chan, Y-J., Garner, S., He, M., Lin, J., Li, X., Sorensen, M., Li, J., Cimo, P., Kuo, C., “Flexible glass substrates for organic TFT active matrix electrophoretic displays,” *SID Display Week*, Los Angeles, May 15-20, 2011.

[3] Wu, K-W., Liao, Y-C., Shiu, J-W., Tsai, Y-S., Chen, K-T., Lai, Y-C., Lai, C-C., Lee, Y-Z., Garner, S., Lin, J., Li, X., Cimo, P., “Color ChLC e-paper display with 100 um flexible glass substrates,” *SID Display Week*, Los Angeles, May 15-20, 2011.

[4] Mourey, D.A, Hoffman, R.L., Garner, S.M., Holm, A., Benson, B., Combs, G., Abbott, J.E., Li, X., Cimo, P., Koch, T.R., “Amorphous Oxide Transistor Electrokinetic Reflective Display on Flexible Glass,” *IDW 2011*, Nogoya, December 2011.

[5] Glaesemann, G.S., Garner, S.M., “Mechanical reliability of thin flexible glass sheets,” *34th Northeast Regional Meeting of the American Chemical Society*, Binghamton, NY, October 5-7, 2006.

[6] Li, X., Garner, S., “CO2 laser cutting of flexible glass substrates,” *ICALEO*, Orlando, October 23-27, 2011.

[7] Garner, S., Merz, G., Tosch, J., Matusick, J., Li, X., Marshall, D., Chase, C., Steiner, J., Yepez, D., Switzer, J., Moschak, P., “Flexible glass substrates for continuous manufacturing,” *FlexTech Flexible Electronics and Displays Conference*, Phoenix, February 7-10, 2011.