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Ultra-Slim Flexible Glass for Electronic Applications

Corning - S. Garner, G. Merz, J. Tosch, C. Chang, J.C. Lin, K.T. Kuo, P.L. Tseng, H.F. Chang, S. Lewis, R. Kohler, L. Tian, L. Simpson, M. Owens, X. Li, S. Logunov
ITRI - S. Huang, J. Shih, A. Wei, M.C. Lin, C.S. Huang, H.T. Lin, C.L. Lin, S.Y. Chang, C.T. Wang, J. Shen, C.H. Hsiao, S.T. Lu, J. Hu, C.T. Liu, H.Y. Lin, W.S. Yang, C.C. Su
CAMM - J. Switzer, J. Steiner

January 7, 2013

Outline

- Electronic device applications
- Mechanical reliability
- Continuous device processing
- Summary

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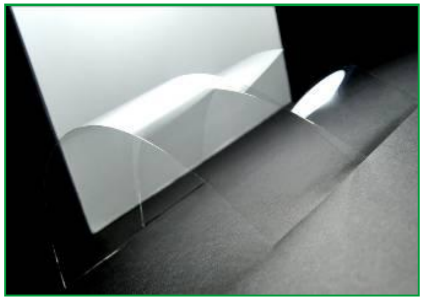
Flexible Glass Enables High-Quality Electronics

Substrate choice critical for device fabrication & performance

- Substrate integrates designs, materials, & processes
  - Essential for overall optimization
  - Glass enables improved resolution, registration, performance, & lifetime
- “Flexible electronics” devices typically focused on thin, light, or conformal
- Corning® Willow™ Glass compatible with sheet-fed and R2R processes
  - Thickness ≤200μm
  - Alkali-free borosilicate composition
  - Optimized for device substrate and hermetic barrier applications

Flexible Glass Sheets



Flexible Glass Web

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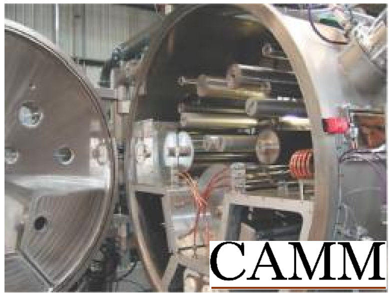
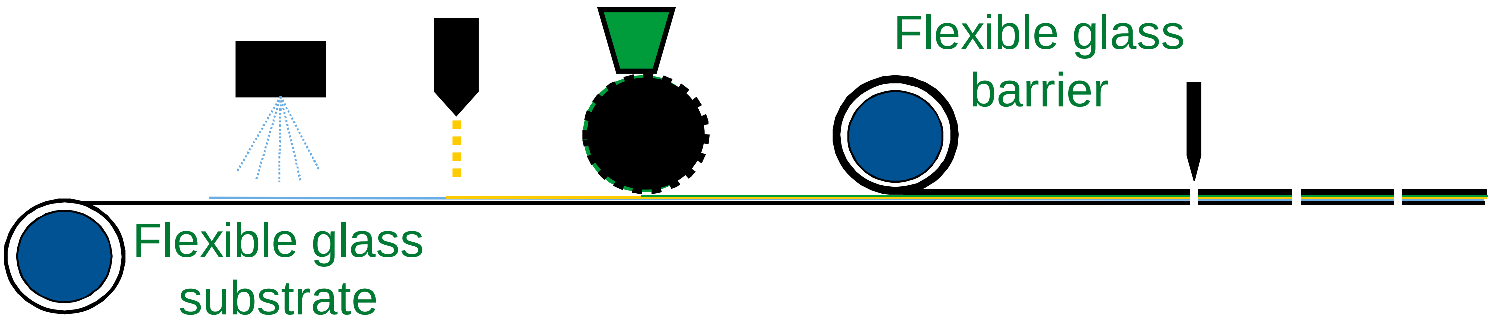
Flexible Glass Continuous Device Fabrication Exists
Demonstrated capabilities for key building block processes

Conveyance

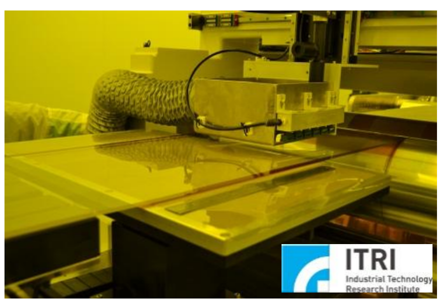
Vacuum Deposition



Coating & Lamination



Photolithography & Patterning



Wet Processing

Printing

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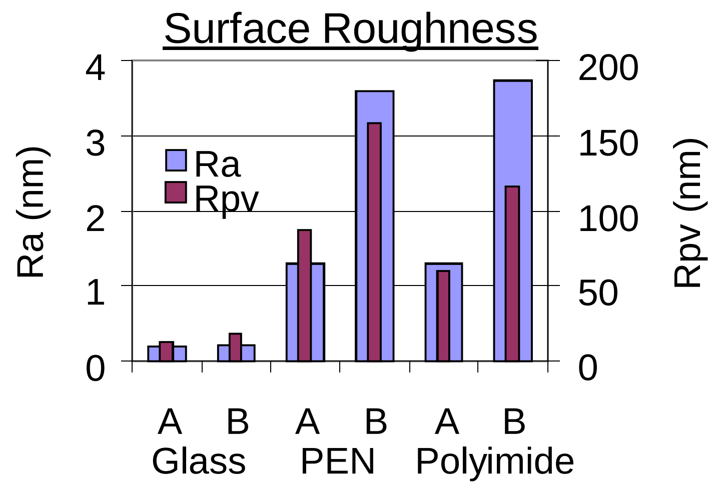
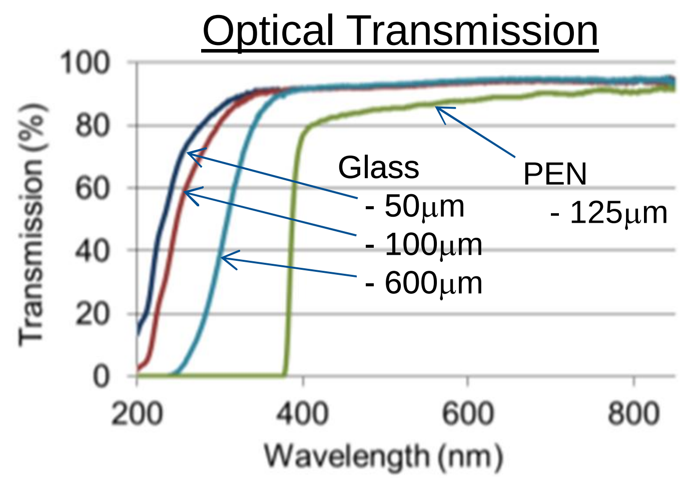
Glass Enables Device Performance Optimization
Flexible glass offers high-quality surface & optical properties

- Device applications include:
  - Displays
  - Touch sensors
  - Photovoltaics
  - Lighting



- Flexible glass benefits include:
  - Surface quality
  - Optical transmission
  - Hermeticity



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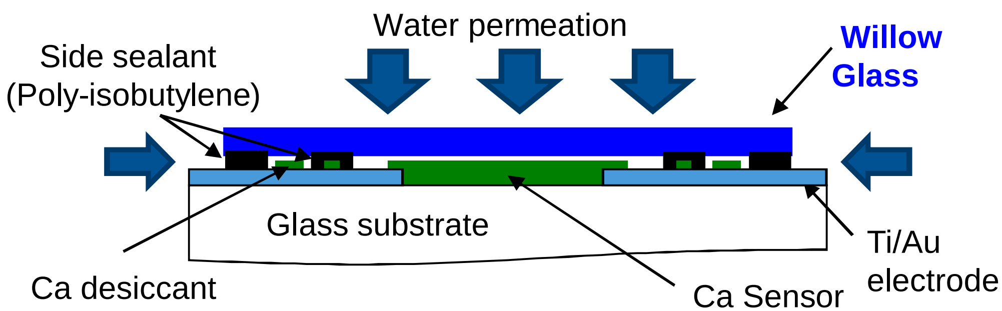
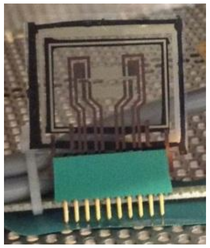
Flexible Glass Provides Superior Barrier Performance

Glass substrates are benchmark for encapsulation technologies

Testing Method	Conditions	WVTR Result	Notes
Mocon: Aquatran Next Generation Prototype	50°C, 100% RH	$<5x10^{-5}$ g/m^2-day	Below system detection limit
Georgia Tech: Ca-patch electrical sensor	50°C, 85% RH	$6x10^{-5}$ g/m^2-day	Limited by edge sealant performance





Ca Sensor

Georgia Tech | emrl Electronics Manufacturing and Reliability Laboratory

Samuel Graham

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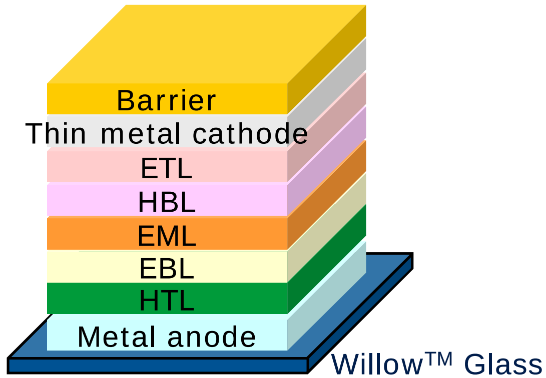
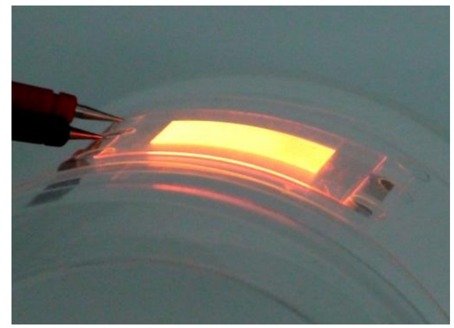
Flexible Glass Enables Overall Device Optimization

Glass is compatible with existing encapsulation methods

- Flexible glass enables hermetic encapsulation of conformal devices



OLED device with 5cm radius



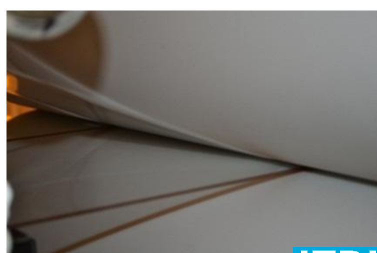
M.Toerker, et al., “Transparent OLEDs for signage and decorative lighting applications,” *LOPE-C 2012*, Munich, June 20, 2012.

- Specific encapsulation method selected to meet overall device requirements
  - Flexible glass compatibility demonstrated with typical encapsulation methods

Vacuum Deposition

CAMM

Coating / Lamination

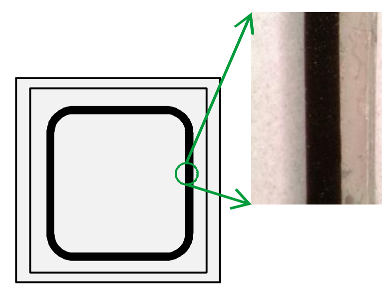


ITRI Industrial Technology Research Institute

Printing

VTT

Frit Sealing



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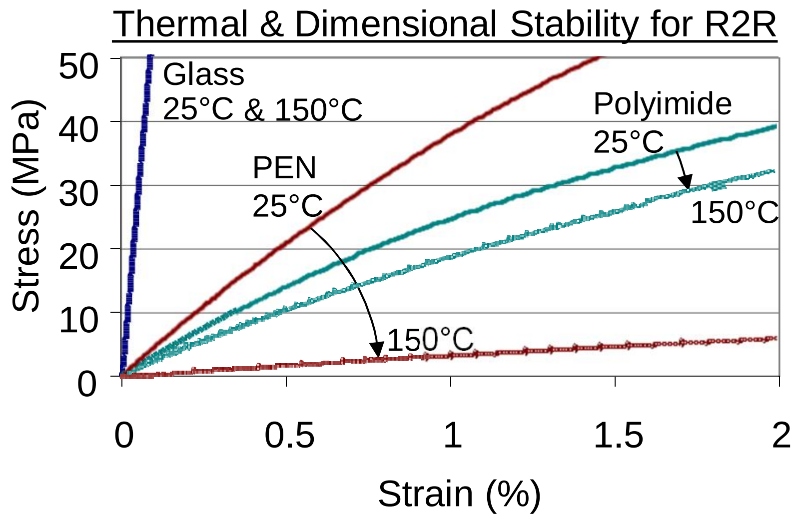
Glass Enables Fabrication Process Optimization

Flexible glass offers dimensional stability & process compatibility

- Flexible glass benefits for device fabrication
  - Thermal capability
  - Dimensional stability
  - Chemical compatibility
- Flexible glass enables layer-layer registration
  - R2R processes
  - Sheet-fed processes



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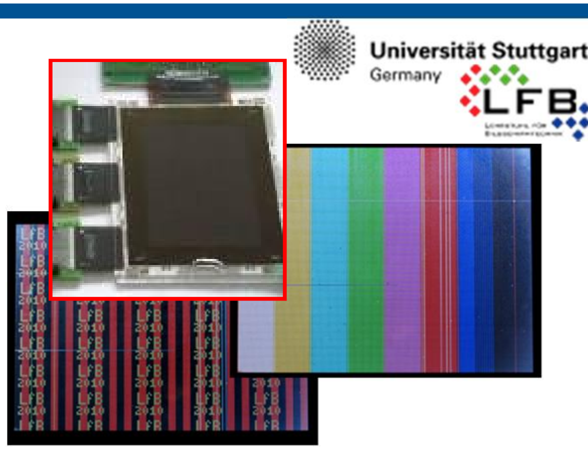
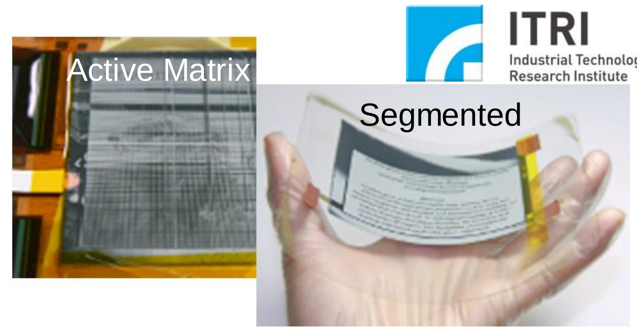
Flexible Glass Enables Thin, Light, Conformal Displays

Capability demonstrated with ≤100μm glass substrates



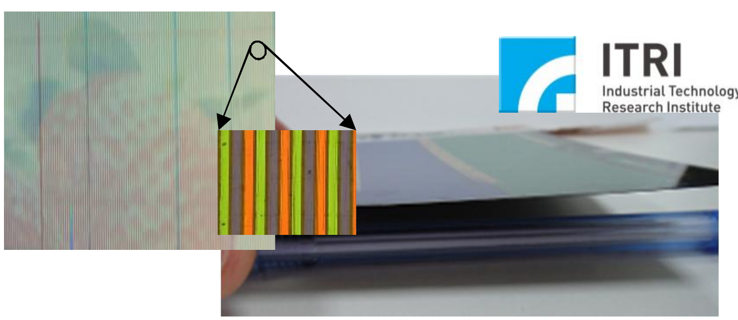
Color LCD, 4” diag., <170μm thick, qVGA

S. Hoehla, et al., “Active Matrix Color-LCD on 75μm Thick Flexible Glass Substrates,” *IEEE J. Disp. Technol.*, vol. 8, pp. 309-316, 2012.



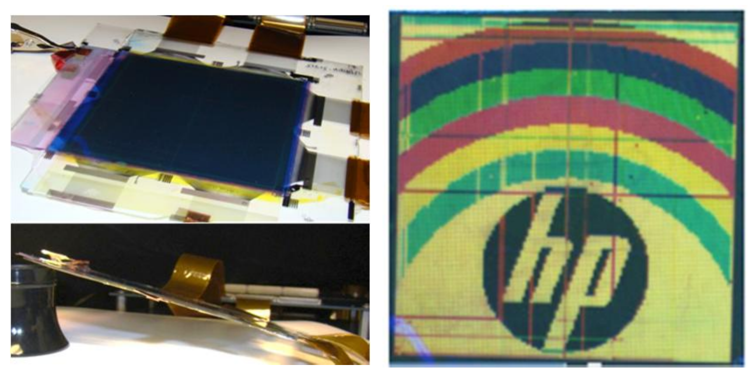
EPD, 4.7” diag., <270μm thick, 170dpi

S. Garner, et al., “Electrophoretic Displays Fabricated on Ultra-Slim Flexible Glass Substrates,” *IEEE J. Disp. Technol.*, vol. 8, pp. 590-595, 2012.



Color ChLCD, 5” diag., <210μm thick, 80ppi

K-W. Wu, et al., “Color ChLC E-paper Display with 100μm Flexible Glass Substrates,” SID 2011.



Color EKD, 3.5” diag., 3-layer stacked, <0.7mm

D.A. Mourey, et al., “Amorphous Oxide Transistor Electrokinetic Reflective Display on Flexible Glass,” IDW 2011.

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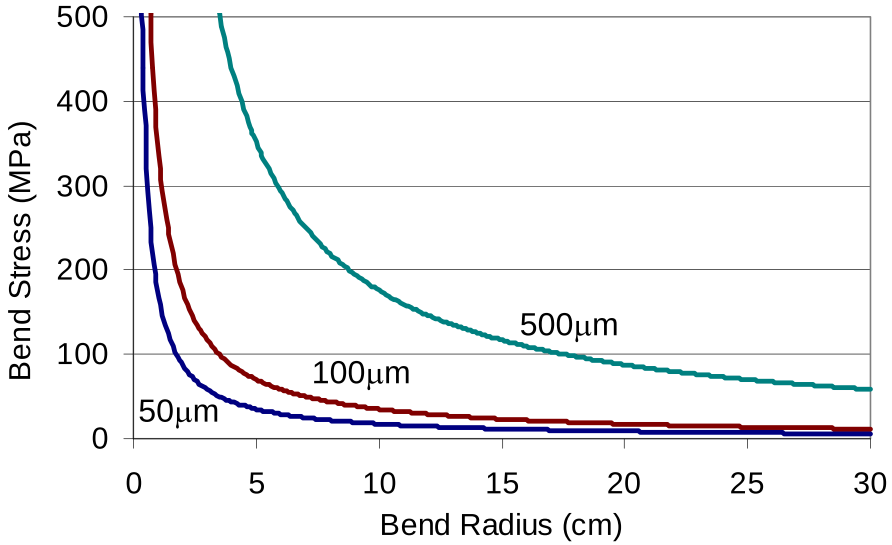
Mechanical Reliability of Flexible Glass

Substrate solutions optimized for continuous processing

- Mechanical reliability of glass understood
  - Fracture mechanics framework: distributions of defects and applied stresses
  - Allowable stress based on model for subcritical crack growth

- Mechanical reliability requires controlling defects and applied stress
  - Providing high-strength glass forming, including surfaces and edges
  - Protecting substrate from damage
  - Managing stresses during conveyance, handling, and application



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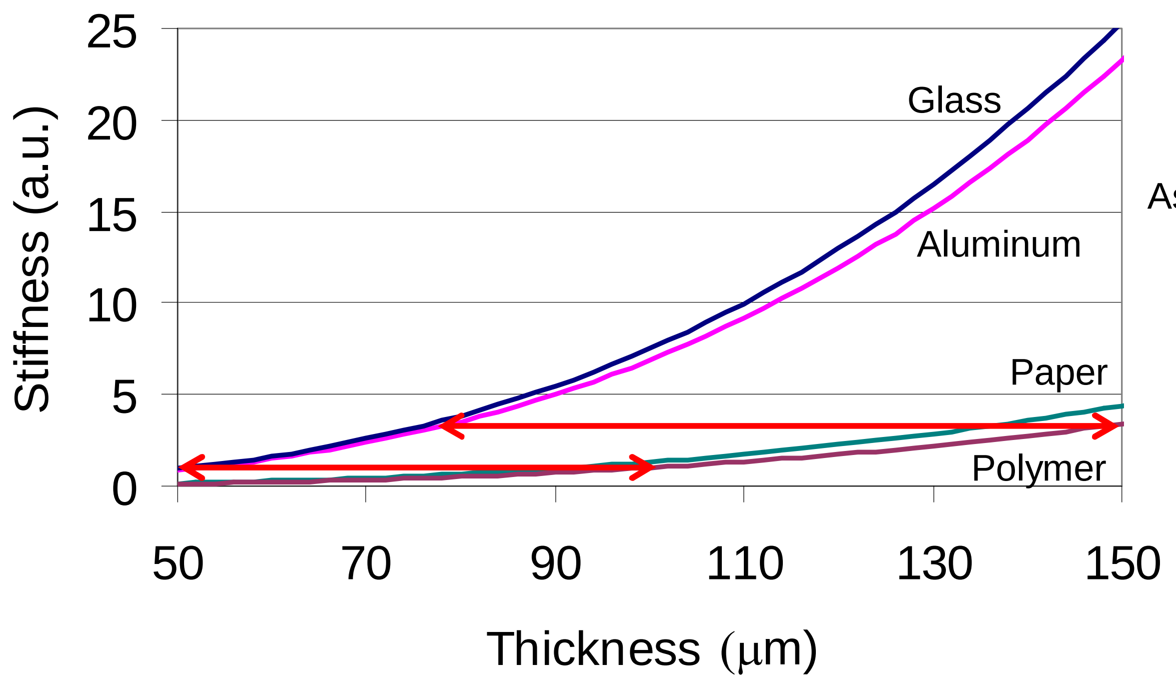
Roller Systems Efficiently Convey Flexible Glass

Glass web stress managed during device fabrication

- Flexible glass bends similarly to other web materials
  - Stiffness ~ E * $(\text{thickness})^3$
- Control stresses through roller handling systems
  - Approach is compatible with sheet-fed or roll-to-roll systems



Assumed modulus values:
Glass = 75 GPa
Aluminum = 69 GPa
Paper = 13 GPa
Polymer = 10 GPa

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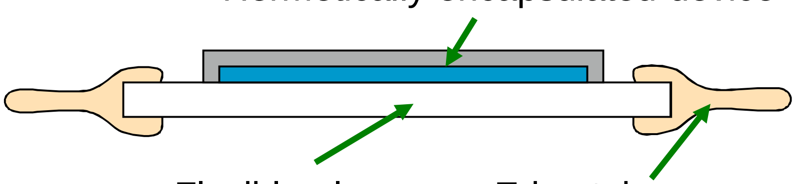
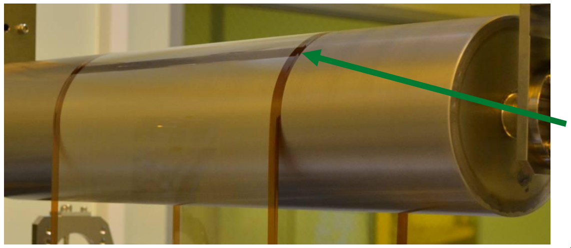
Proper Handling & Coatings Prevent Contact Damage
Edge tabs enable device fabrication directly on glass surface

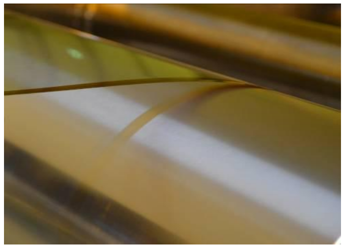
- Mechanical reliability solutions optimized for specific scenarios
- Minimizing contact damage required for reliability
  - Packaging, shipping
  - Device manufacturing
  - In-service use
- Edge tabs protect glass web during conveyance, winding, and device fabrication

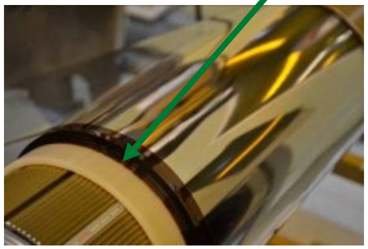
Flexible Glass Web Cross-Section



Glass Web Conveyance - 330mm Width





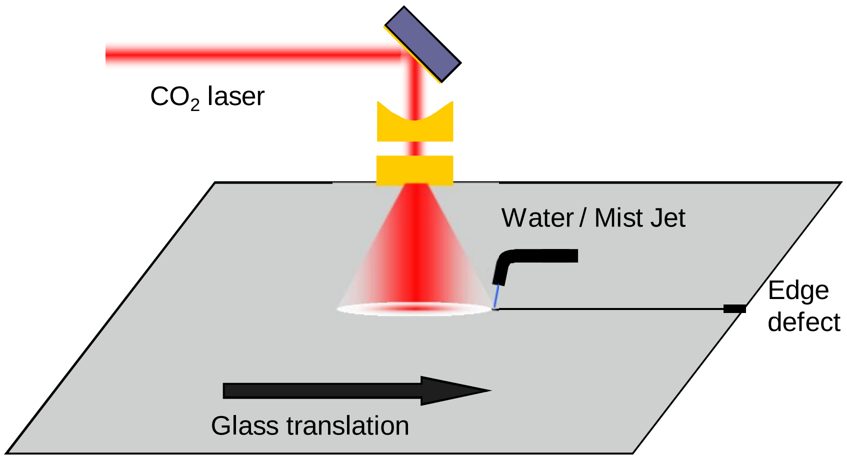


CO_2 Laser Processes Singulate Flexible Glass Devices

Utilizes tensile stress to propagate a crack along cutting path

- Laser cutting & mechanical scribe options exist for device singulation
- Laser process based on tensile stress generated by heating & cooling

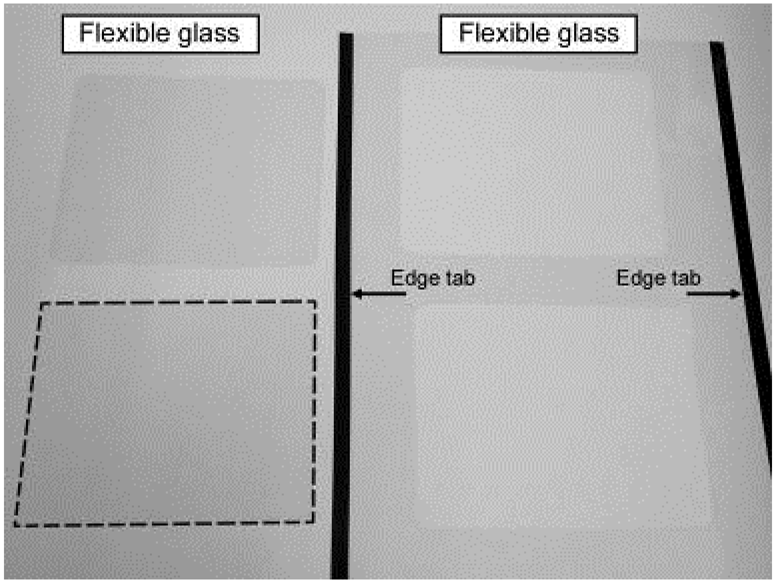
CO_2 Laser Cutting of Flexible Glass



Free-Shape Cutting Possible

Round Corners	Wafer with Flat Edge	Square Corners
		

Substrates Singulated from Glass Web



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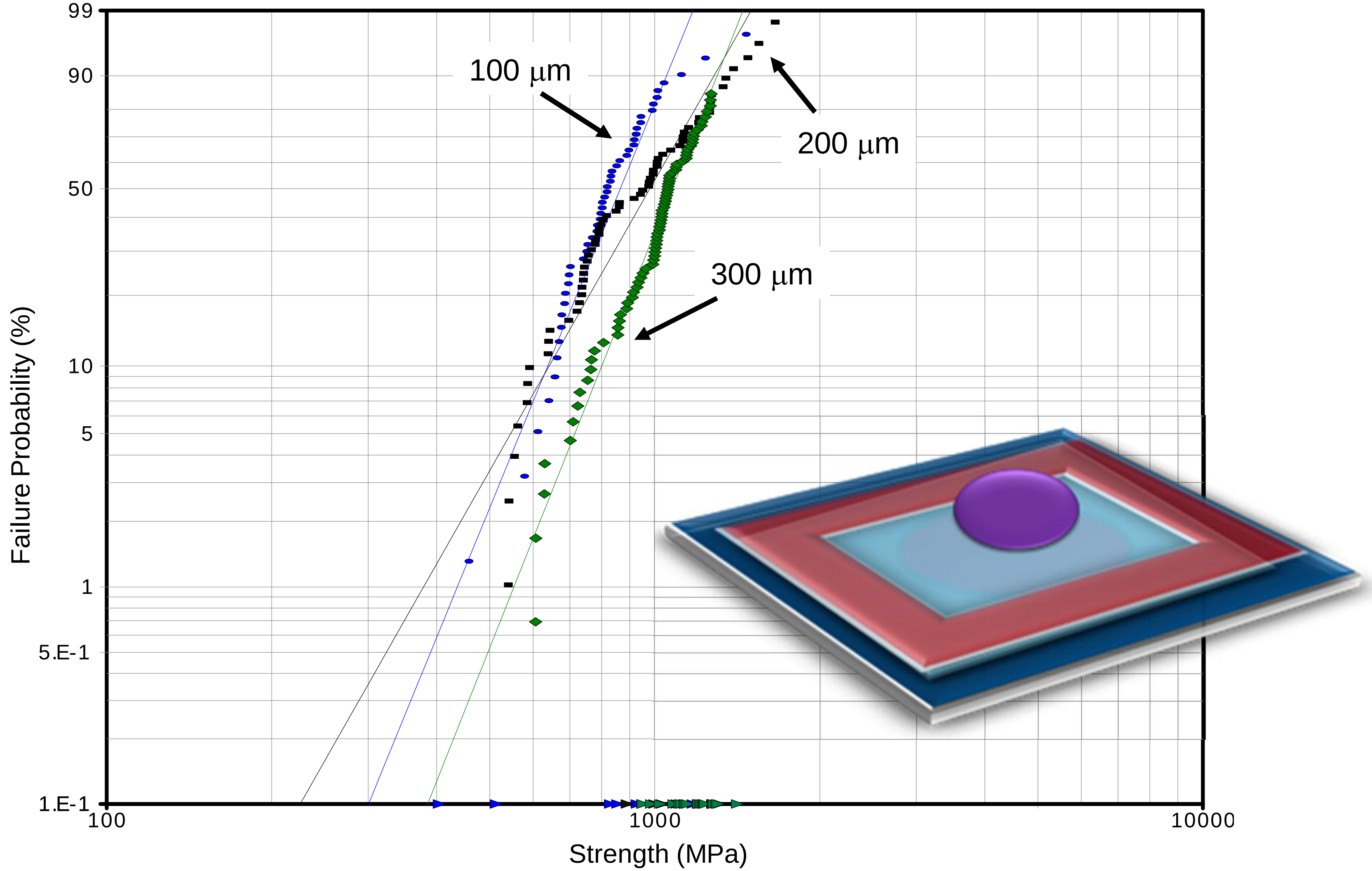
Glass Surface Strength is Independent of Thickness

New test methods developed for flexible substrates



G.S. Glaesemann, et al., "The Strength of Thin Fusion Drawn Glass Sheets," *11th ESG Conference 2012, Maastricht*, The Netherlands

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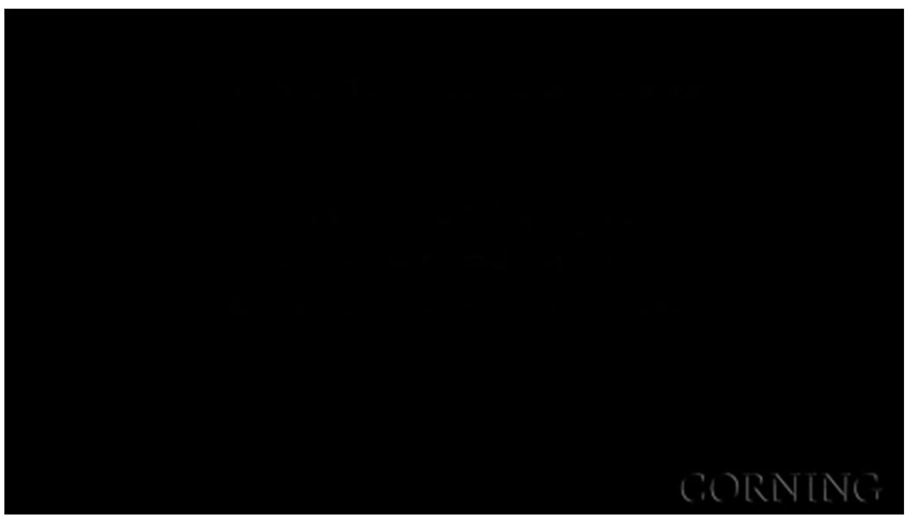
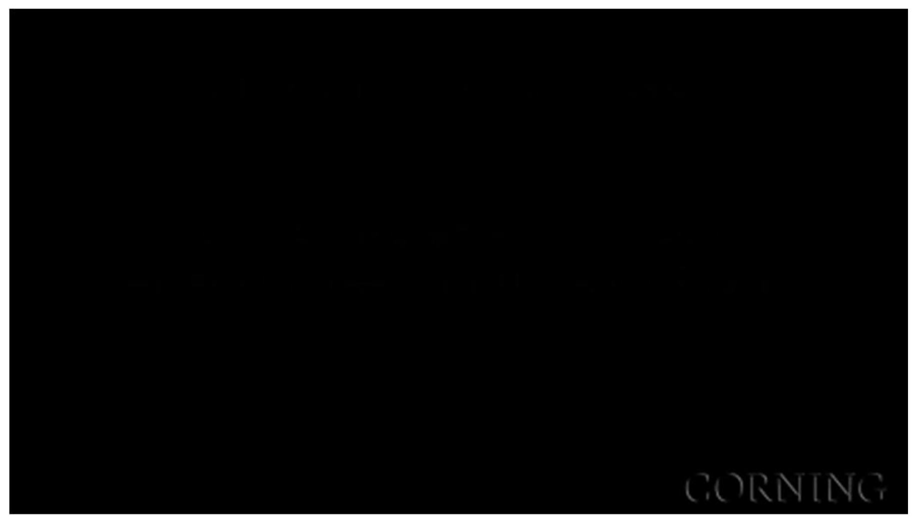
Willow Glass Reliability Enables Device Fabrication
Reliability based on managing stress & defect distributions

Willow Glass Mechanical Reliability



Willow Glass Roller Conveyance



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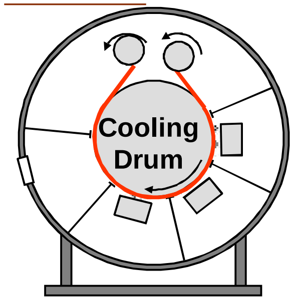
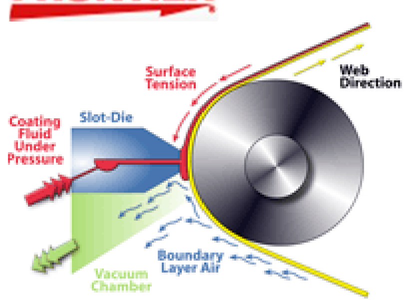
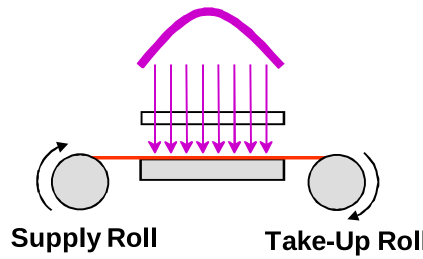
Flexible Glass is Compatible with R2R Processing

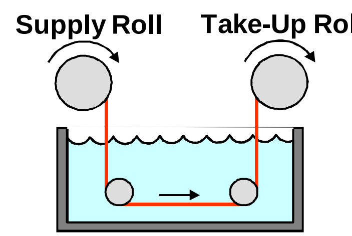
Demonstrated continuous photolithographic patterning of ITO

ITO Deposition	Slot Die Coating	Exposure	Development & Etch
CAMM	FRONTIER	CAMM	CAMM









S. Garner, et al., “Flexible glass substrates for continuous manufacturing”, Flexible Electronics and Displays Conference, February 9, 2011.

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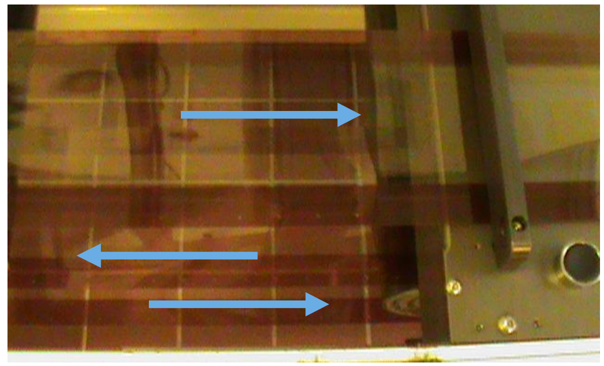
Glass Web Conveyance Demonstrated in R2R Systems

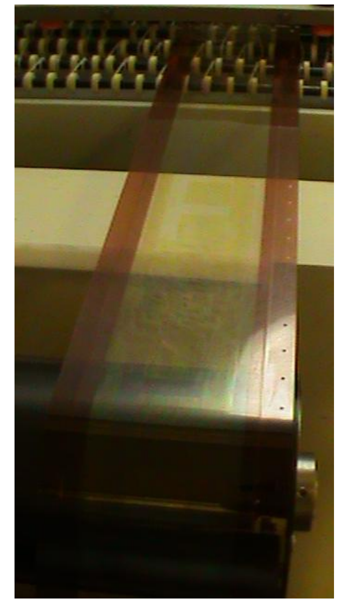
Compatible with vacuum deposition, slot-die, and wet processes

Web Un-Wind

Dancer



Conveyance into Wet Etch



The authors would like to acknowledge the financial support of the FlexTech Alliance under Army Research Laboratory program W911NF-09-3-0001.

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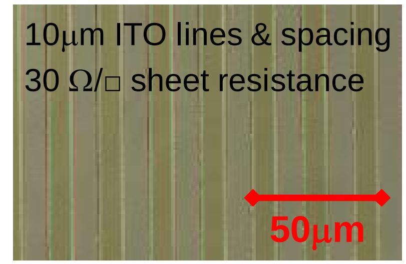
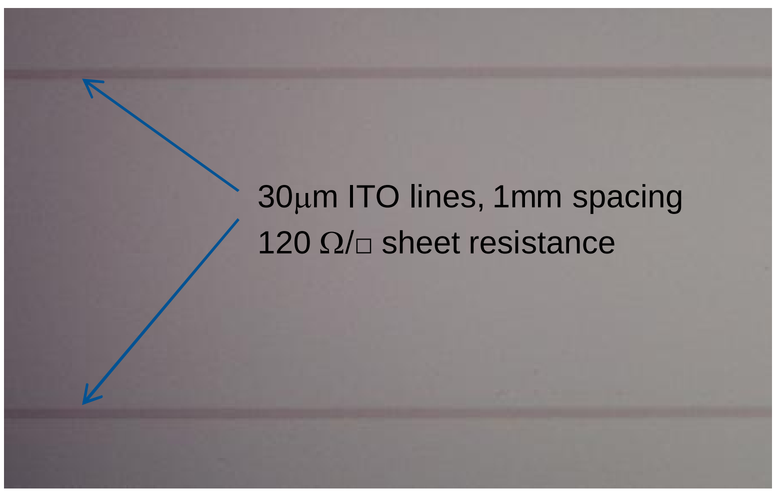
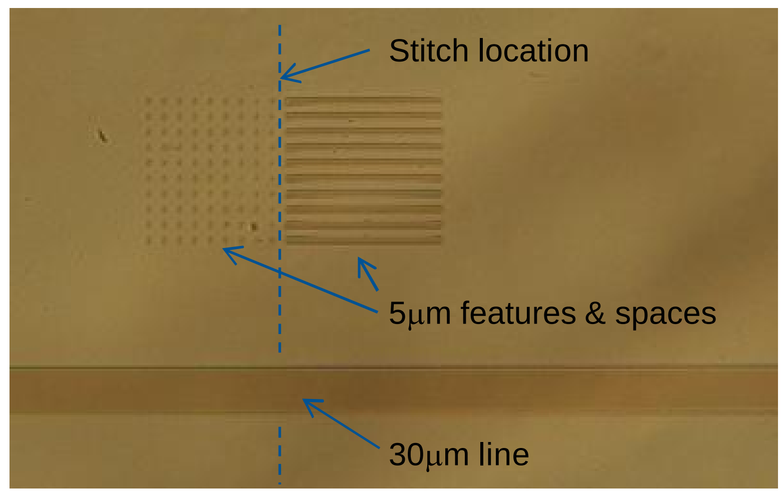
Glass Web Capabilities Exist for Device Fabrication
R2R processes meet resolution & registration requirements

- Demonstrations utilized CAMM ITO deposition and patterning capabilities
- Patterned 30Ω/□ ITO with 10μm lines & spaces
- Patterned 120Ω/□ ITO with 30μm lines
  - 250mm lengths created by stitching 5 exposures
    - Stitch location not observable under microscope
  - Feature sizes down to 5μm







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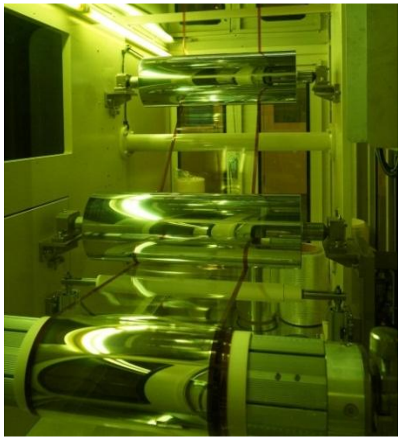
R2R Slot Die Coating of Electronic Materials
Demonstrated 275mm width coating on 330mm web

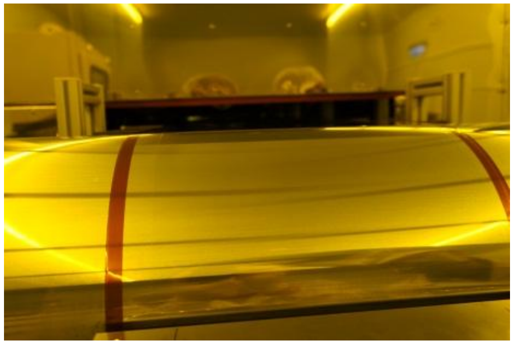
- 5m/min conveyance demonstrated
- Representative PEDOT material coated
  - 100°C and 150°C 2-zone drying oven
  - Resistance: 1000 Ω/sq.
  - Transmittance: 92.4%
  - Haze: 0.2

Glass Web R2R Slot Die Coater

Glass Web Rewind Module



Coated Glass Web Exiting Oven



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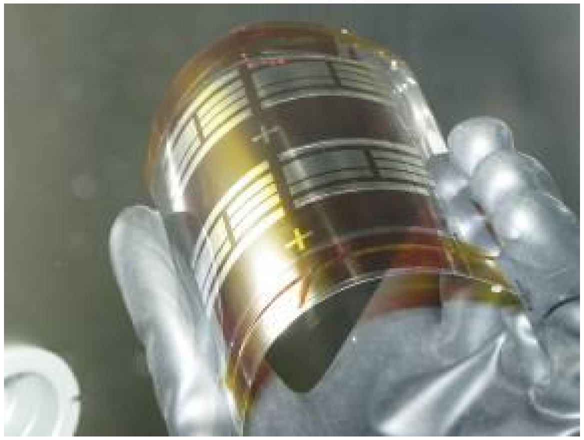
Willow Glass Compatible with Gravure Printing
Gravure printed organic PV on flexible glass

- 100mm x 100mm flexible glass coupons taped to polymer web
- R2R gravure printing of PEDOT:PSS and P3HT:PCBM using ROKO pilot line
  - 8m/minute line speed (equipment limit)
  - 130mm diameter gravure cylinder
  - Printed continuous surface layer
    - Manually created through-holes for ITO contact
- Cathode layer evaporated through shadow mask

ROKO R2R Pilot Line

Flexible Glass OPV



S. Garner, et al., "Ultra-Slim Flexible Glass Substrates for Continuous Device Fabrication," Prinse'12 Industry Seminar, Oulu, Finland.

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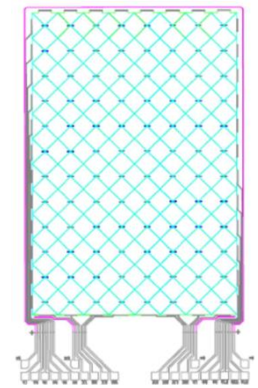
Glass Web R2R Touch Sensor Fabrication

Flexible glass is compatible with required individual processes

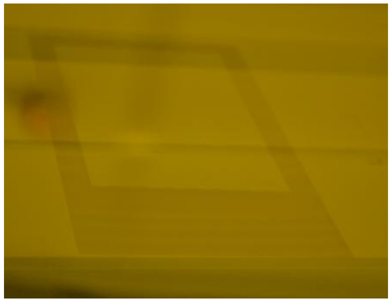
- Touch sensor targeted as representative R2R device process
  - ITO coating
  - Laser ITO patterning
  - Screen printing of frame wire, dielectric, bridge
  - Cover film lamination

3.5-inch Touch Sensor

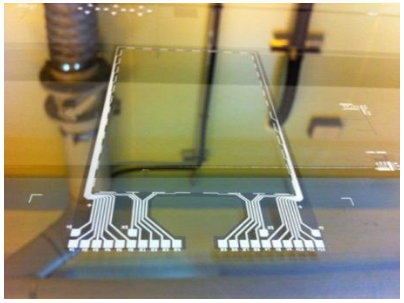


Vacuum Deposition

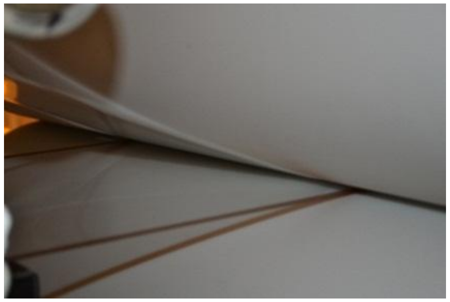
Laser Patterning



Screen Printing



Film Lamination



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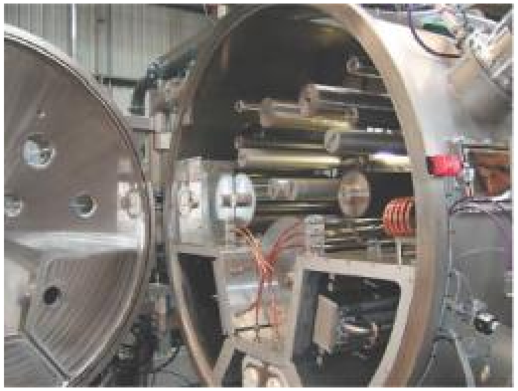
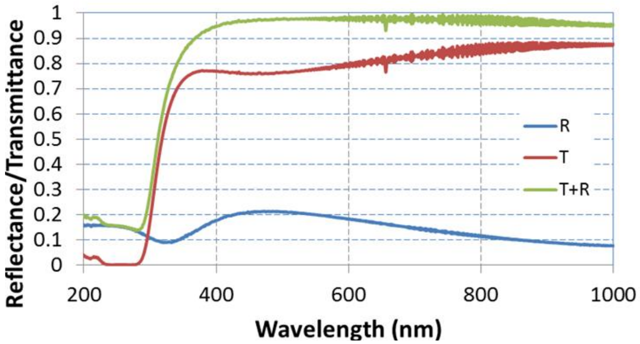
R2R Thin Film Vacuum Deposition on Flexible Glass
Demonstrated elevated temperature ITO sputtering

- Glass web: 330mm width, >40m length
- Deposition with GVE Optilab system
  - 175°C deposition temperature
  - 0.3m/min web speed
- 50 Ω/sq ITO layer, 70nm thick
  - 100nm thick SiO_2 intermediate layer
  - Thin film stack not optimized for transmission
- <3% sheet resistance variation on glass web
  - >250mm width x >10m length measured

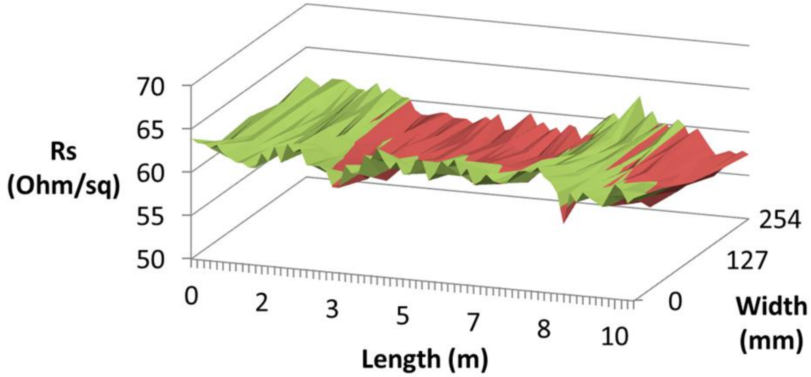
GVE Optilab R2R Sputtering System



Optical Transmission



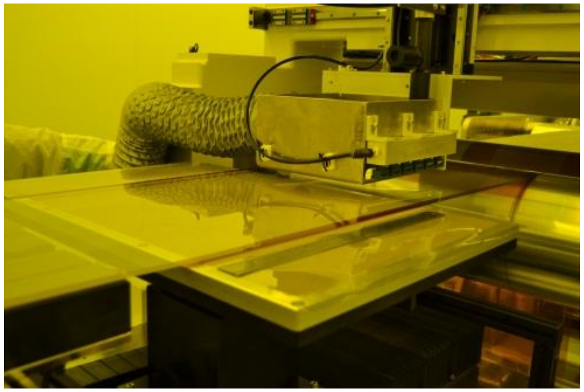
ITO Sheet Resistance Uniformity



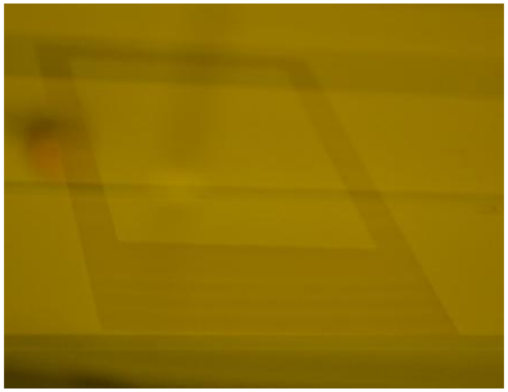
R2R Laser Patterning of ITO-Coated Glass Web
Process maintains flexible glass mechanical reliability

- ns-pulsed 1064nm YAG laser ablation process
  - As-deposited ITO Ra = 1.8nm
  - Ablated ITO Ra = 3.1nm
- Vacuum stage maintains web stability during patterning
  - Step & repeat procedure
  - Continuous unwind / rewind possible by incorporating accumulator
- Demonstrated 30µm ± 3µm lines and spaces

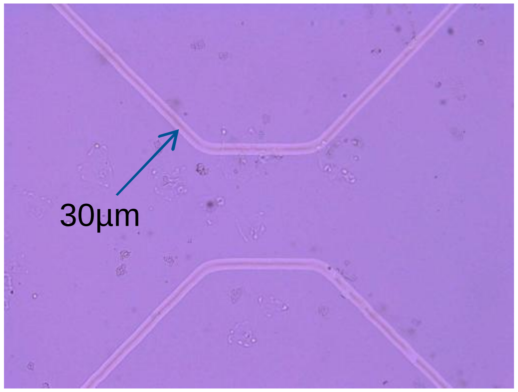
R2R Laser System



Touch Sensor Pattern



ITO Conductor Line



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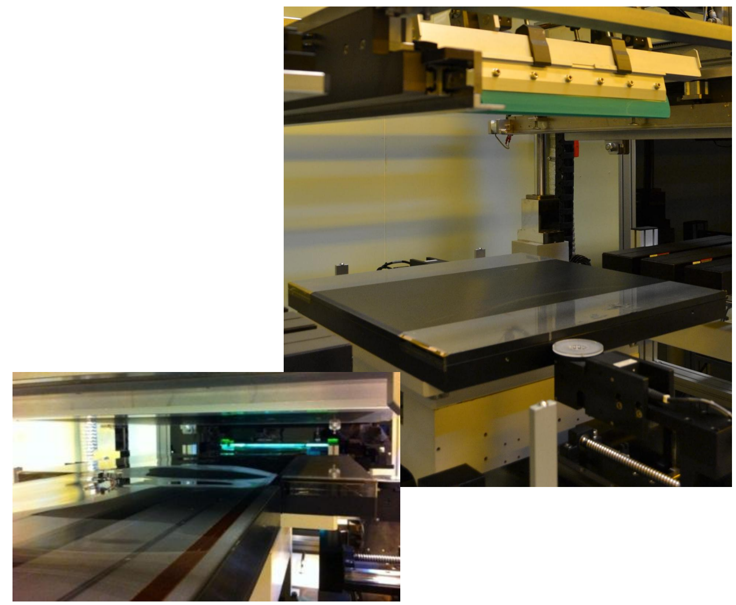
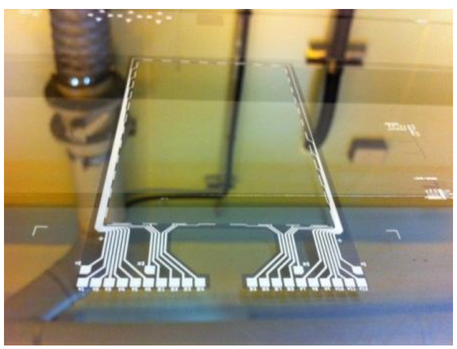
R2R Screen Printing of Dielectric & Ag Conductor
Flexible glass is compatible with multi-step R2R process

- Step & repeat screen printing process
  - Vacuum stage maintains stability during printing
  - <50µm layer-layer registration accuracy
- UV-curable acrylate dielectric
  - 10-20µm thickness
- Ag-ink conductor lines and bridges
  - 110µm width, 15µm height
  - 110°C thermal cure

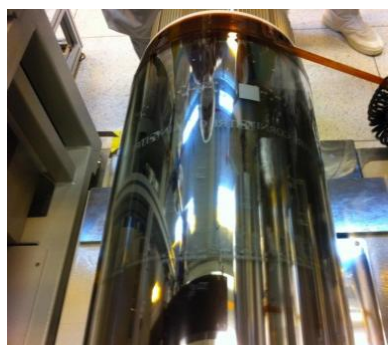
R2R Screen Printing



Touch Sensor Pattern



Glass Spool after Printing



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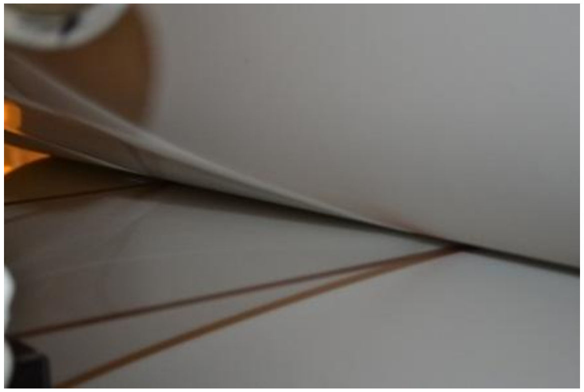
R2R Film Lamination to Glass Web
Demonstrated continuous coating process for flexible glass

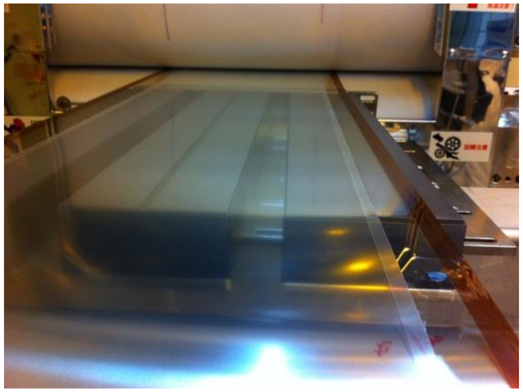
- Flexible glass web compatible with nip roll lamination
  - Multi-layer web re-wound onto 6-inch core after lamination

- PMMA-OCA film laminated to 100µm flexible glass web
  - Protective release liner - 25µm
  - PMMA film - 175µm
  - OCA - 100µm

R2R Lamination



Laminated Glass Web & PMMA



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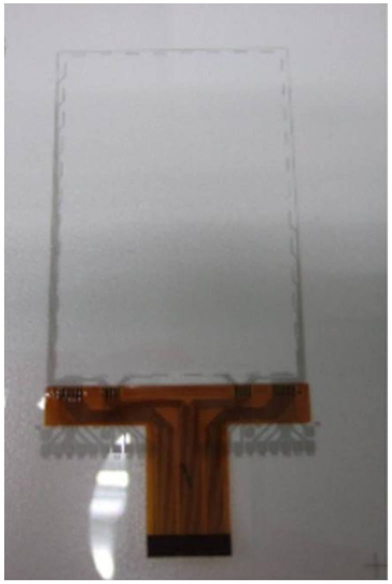
Glass Web is Compatible with Integrated Process
Flexible glass 3.5” multi-touch sensor fabricated

- Demonstrated processes with glass web
  - ITO deposition
  - Laser patterning
  - Screen printing
  - Lamination
- Additional processes for device assembly
  - Singulation
  - FPC-IC bonding

Sensors on Willow Glass Web

Willow Glass Touch Sensor



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Summary

- Flexible glass offers advantages for device designs, materials & processes
  - Includes optical & surface quality, dimensional & thermal stability, hermeticity
  - Enables high-performance active devices
- Mechanical reliability of glass understood
  - Form with high initial strength & minimize defect creation
  - Manage stresses with appropriate handling & conveyance
  - Optimized solutions are application specific
- Flexible glass is compatible with sheet & continuous processing
  - Demonstrated high-quality flexible glass displays
  - Demonstrated R2R process compatibility of glass web

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