Fundamentals of Glass Technology & Applications for Advanced Semiconductor Packaging

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Corning Incorporated

Course Outline

1. Fundamentals of Glass

I. What is Glass?

II. Overview of Glass Attributes

2. Glass Properties and Manufacturing

I. Glass Composition

II. Melting & Forming Processes

III. Secondary Processes

IV. Glass Handling

3. Fundamentals of Glass-Ceramics and Applications

4. Select Applications and Markets

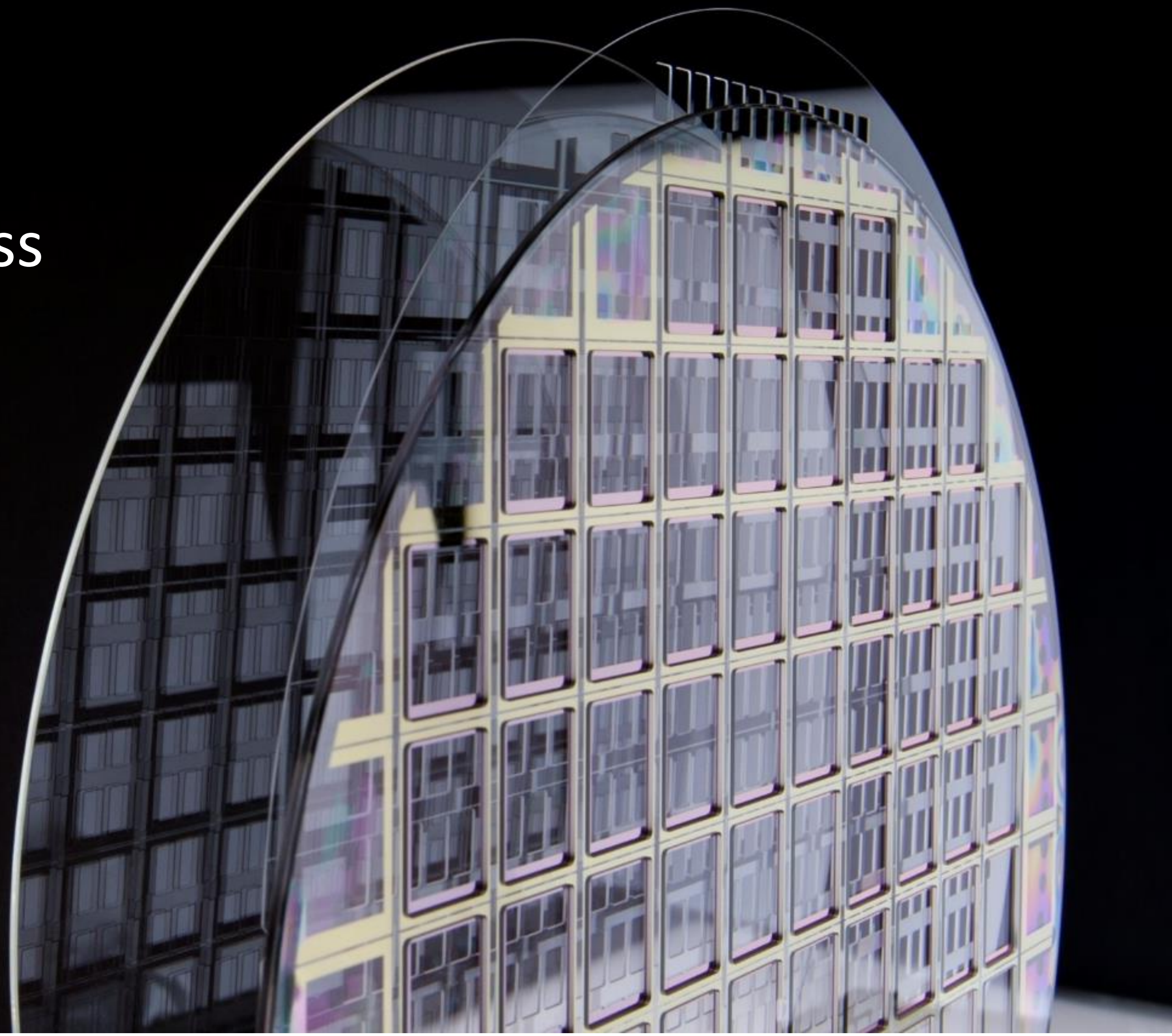
I. Consumer Device Overview

II. Glass Carriers

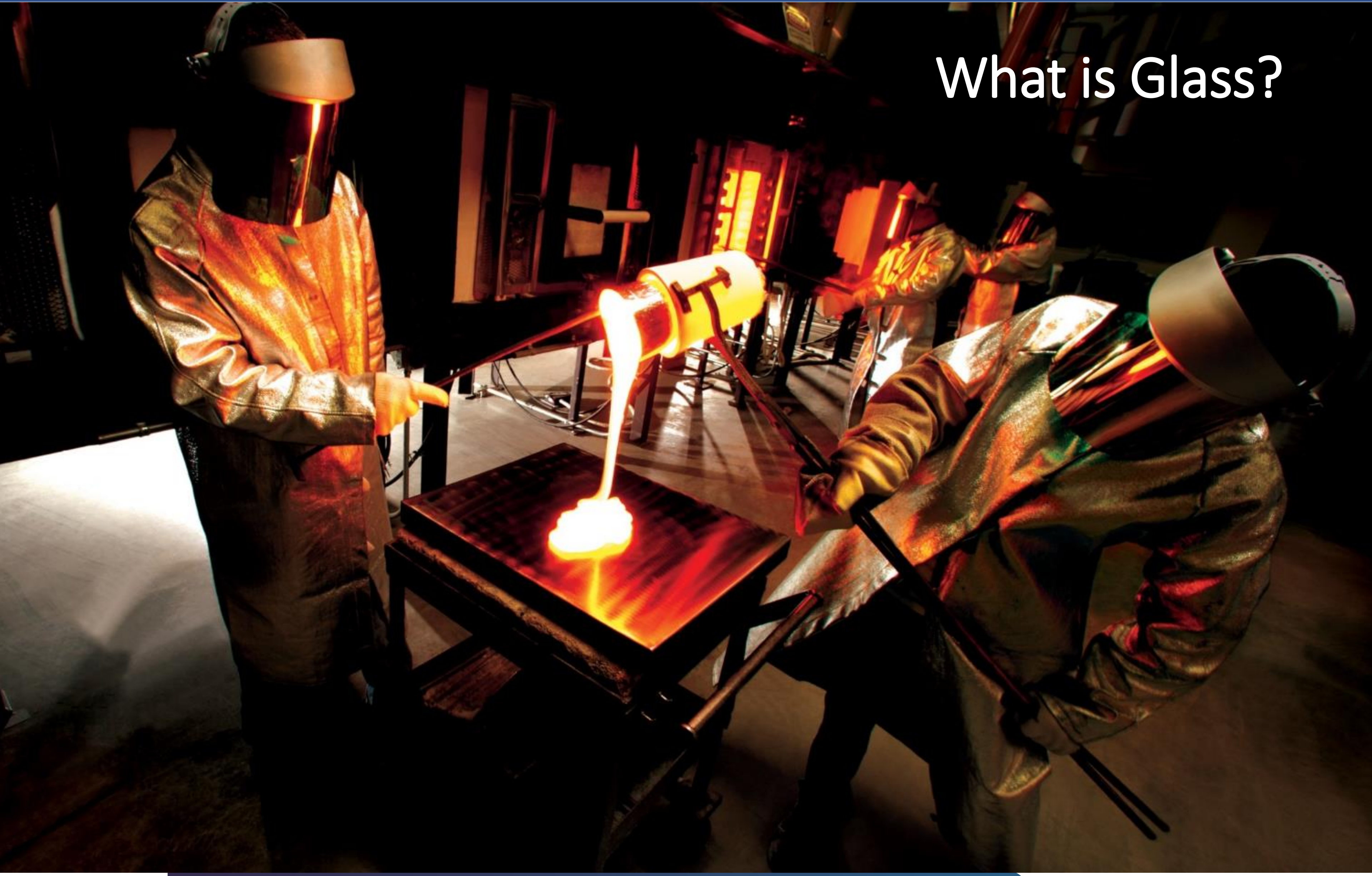
III. Through Glass Vias

1. Fundamentals of Glass

- What is Glass?
- Overview of Glass Attributes



What is Glass?



Glass has been in use for over 5000 years - one of the earliest topics of materials science!

- Soda-lime silicate glass (nominally window glass) has been made for ~5000 years
  - Early artifacts show substantial composition sophistication—origins may be much earlier
- Today manufacture of soda lime for windows, bottles, etc. dwarfs all other types of glass manufacturing combined
  - A typical float glass plant produces 300-400 tons of glass ***per day***

8th Century B.C.E. glass jug

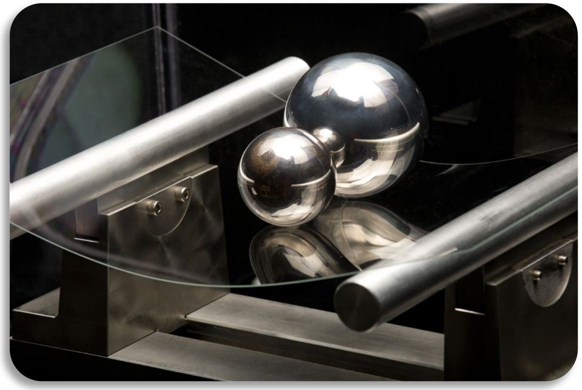
Image from www.ancientskyscraper.com

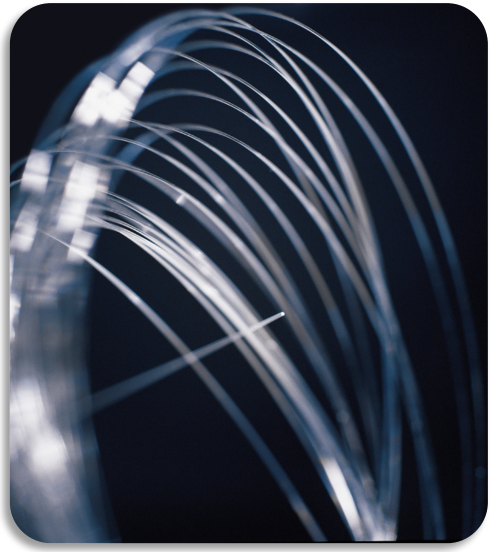
Glasses can be exceptionally tough....

...or exceptionally flexible....

Corning® Gorilla® Glass

- **Thermal tempering**
  Ion-exchange





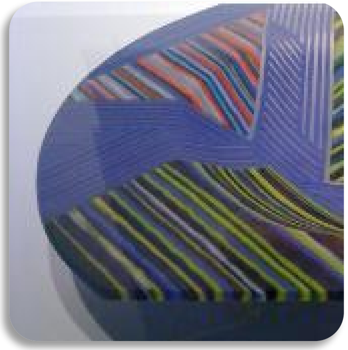
Fiber Optics

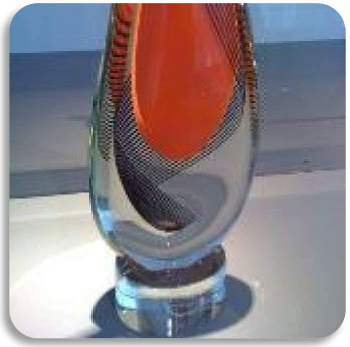
Flexible Displays

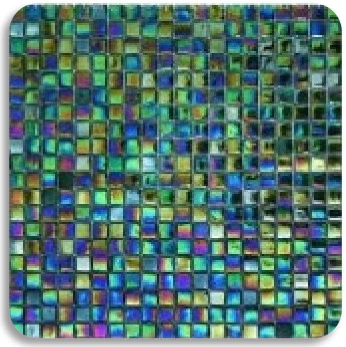
Glass can be colorless…

Substrates and Superstrates
(e.g. Carrier for packaging, Optical elements)

Or colorful…







Decorative and artistic articles

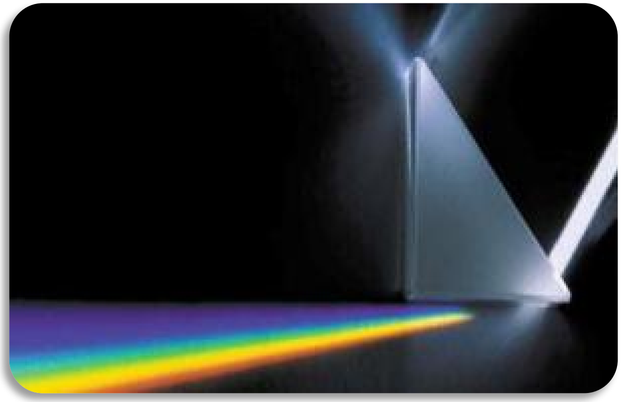
You can color glass via staining

- Staining (*selective ion exchange*) followed by reduction can be used to *stain the surface* of glass articles.

Silver stain (yellow)

Copper stain (ruby red)

Glasses can refract or block light

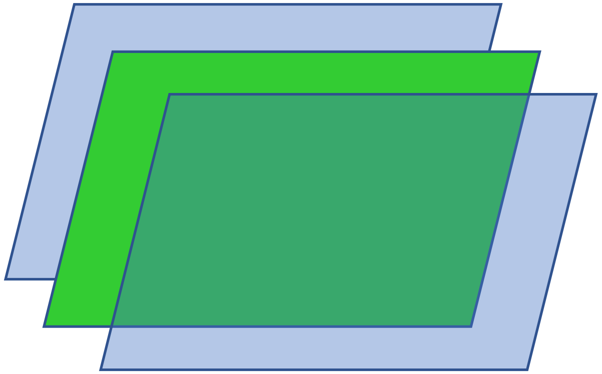


High index glasses strongly refract light, producing sharp black & white and “rainbow” effects.

Polarcor™ passes light polarized in the right sense and blocks light that is not.

Glass can be formed into sheets…

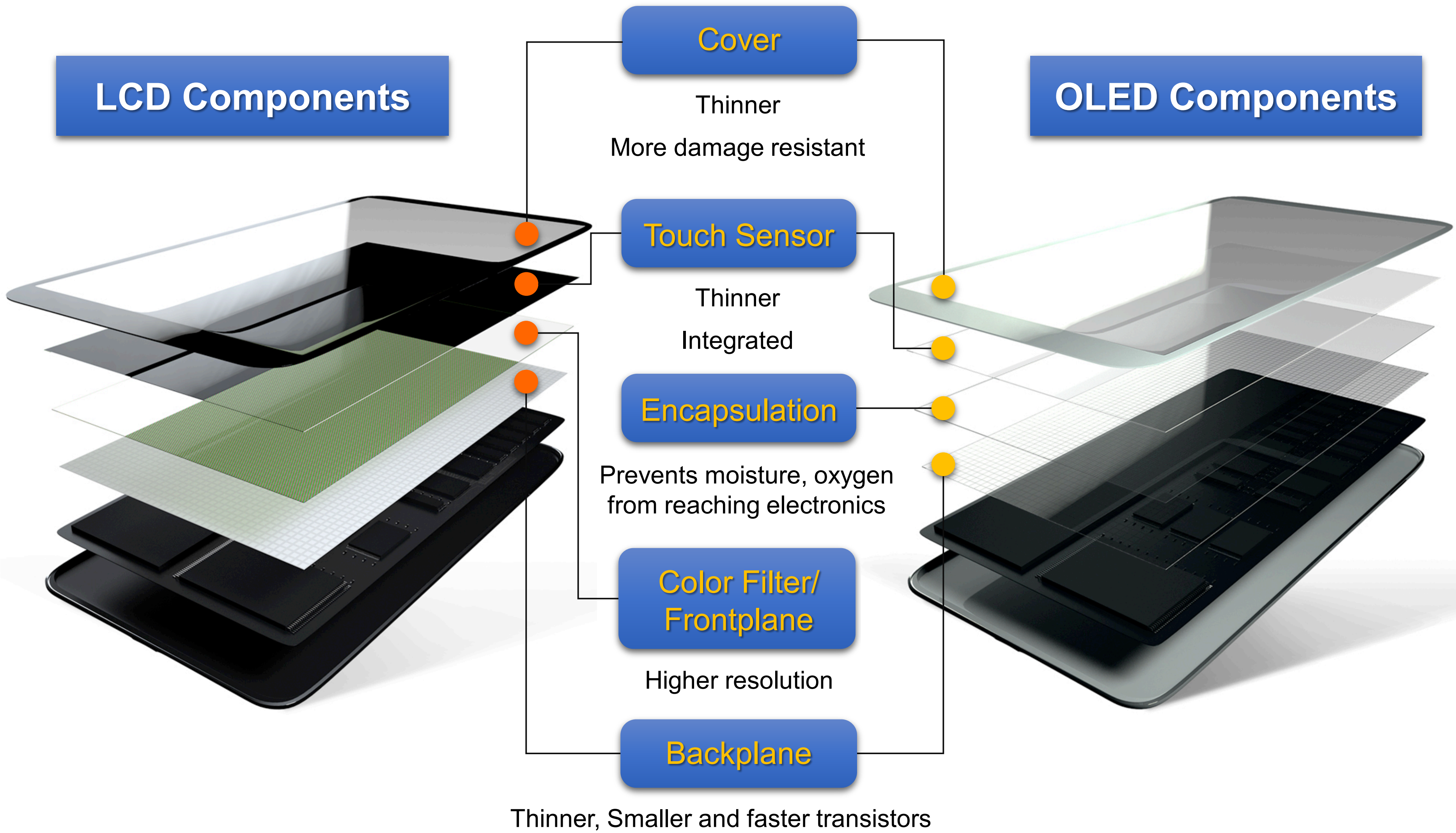
- Pristine surface of fusion can be used for laminates!



Laminated Sheets

…and also 3D shapes

Glass is integral to key display technologies



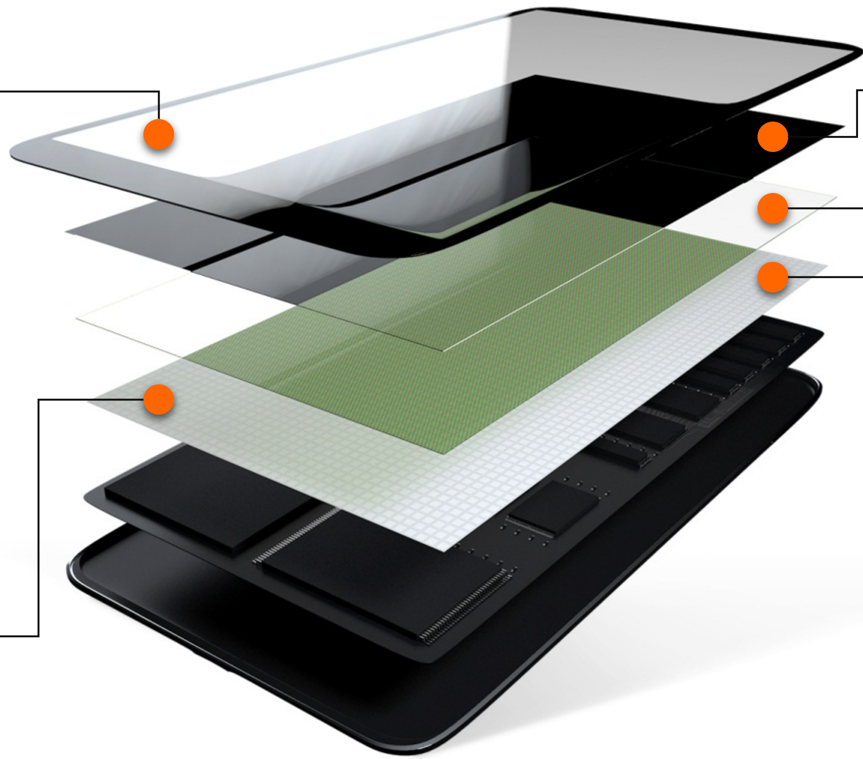
Each component requires specialty glasses

Corning® Gorilla® Glass

Cover Glass

Corning® Willow® Glass

Substrate Glass
(Touch sensor, color filter,
TFT backplane)



Corning Lotus™ NXT Glass

Substrate Glass
(OLED, LTPS-LCD displays,
Oxide-TFT backplane)

EAGLE XG® Slim Glass

Substrate Glass
(a-Si backplane)

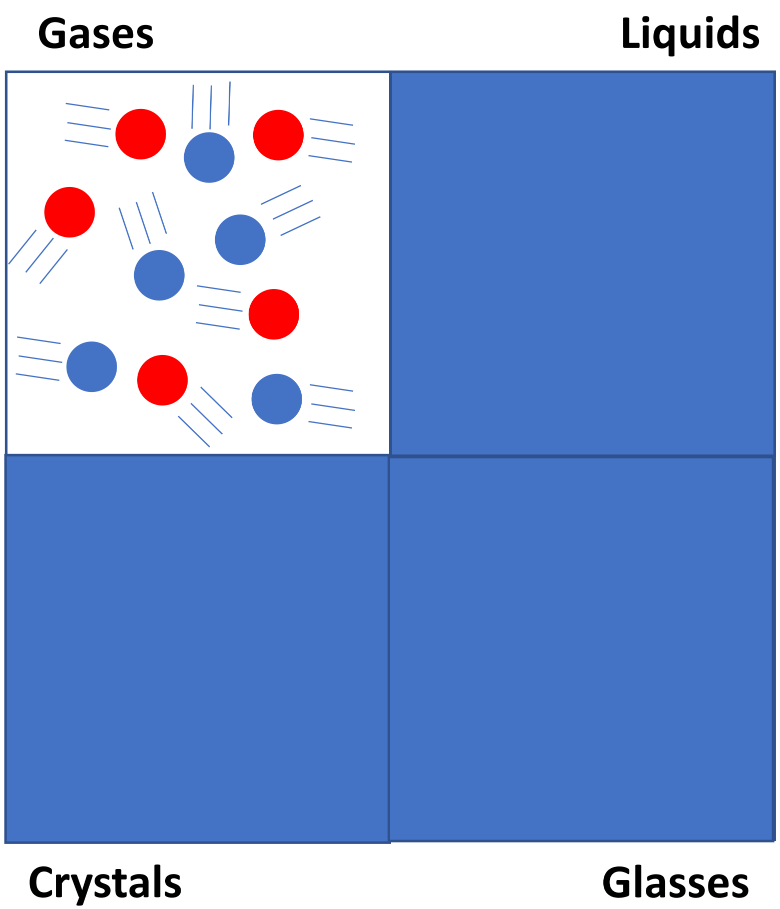
Enabling complex electronic circuits with greater functionality

What is glass?

- Glass:
  - Is often simply defined as a non-crystalline solid or as a rapidly cooled liquid that gradually becomes a solid*
  - Can be formed into objects while still a viscous liquid
  - Has an amorphous (random) molecule level network structure

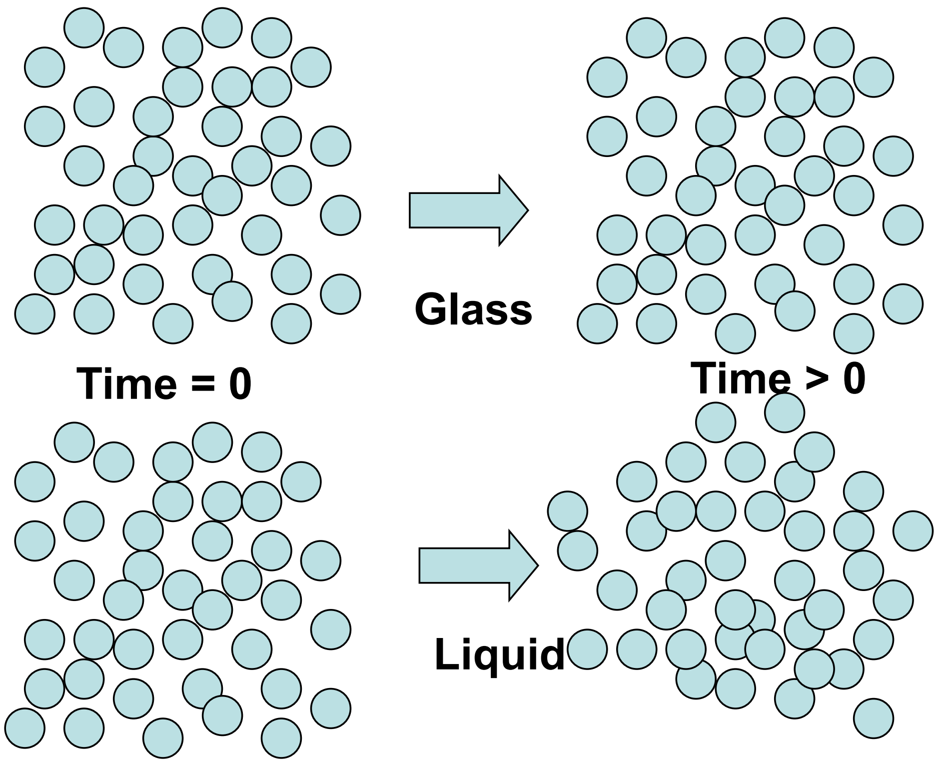
* “Rapidly” and “gradually” are relative terms.

There are several forms (phases) of matter



Form	Characteristics
Gases	Discrete particles that don't stick to one another. Plasmas are gases of ions.
Liquids	Particles are in sliding contact with each other
Crystals	Atoms occupy fixed, well-defined positions
Glasses	Atoms are at fixed positions, but their sites are not well-defined

The structure of a liquid and corresponding solid glass look similar

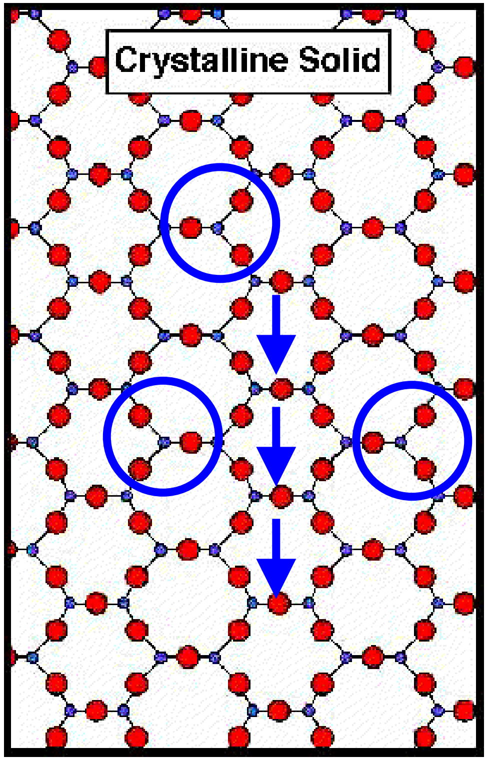


Because of thermal motion, the liquid state structure changes dramatically with time, while the solid state structure does not.

From A. Clare (2006)

How do glasses differ from crystals?

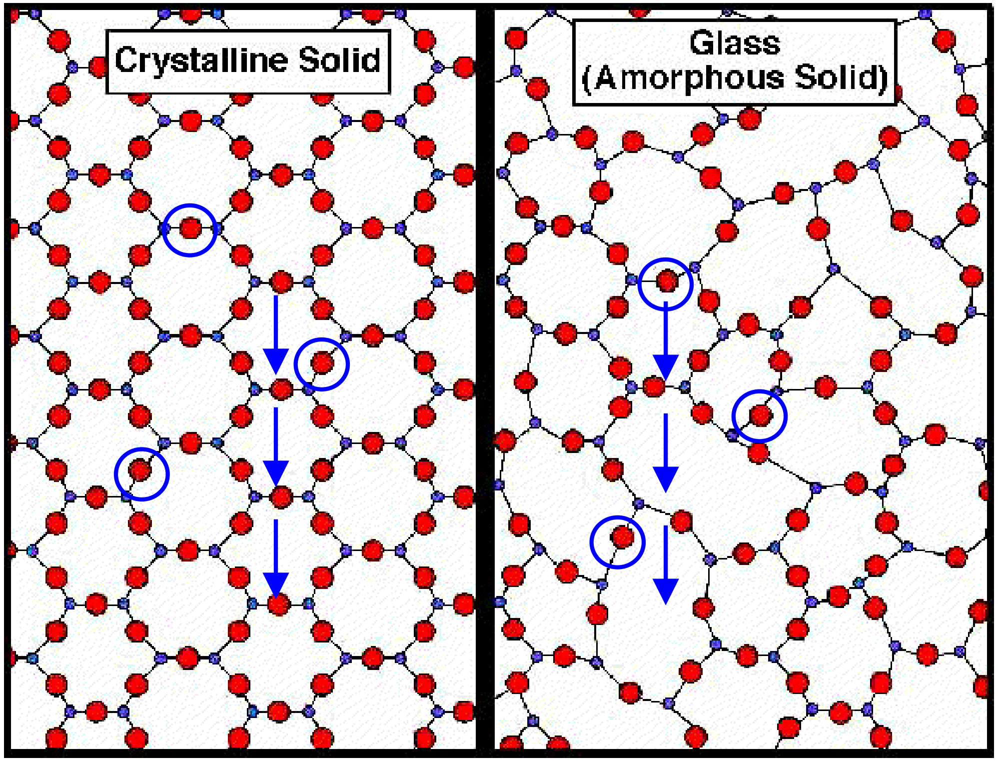
If you move in particular directions, you find identical atoms in identical sites



Two-dimensional crystal lattice.

How does glass differ from crystals?

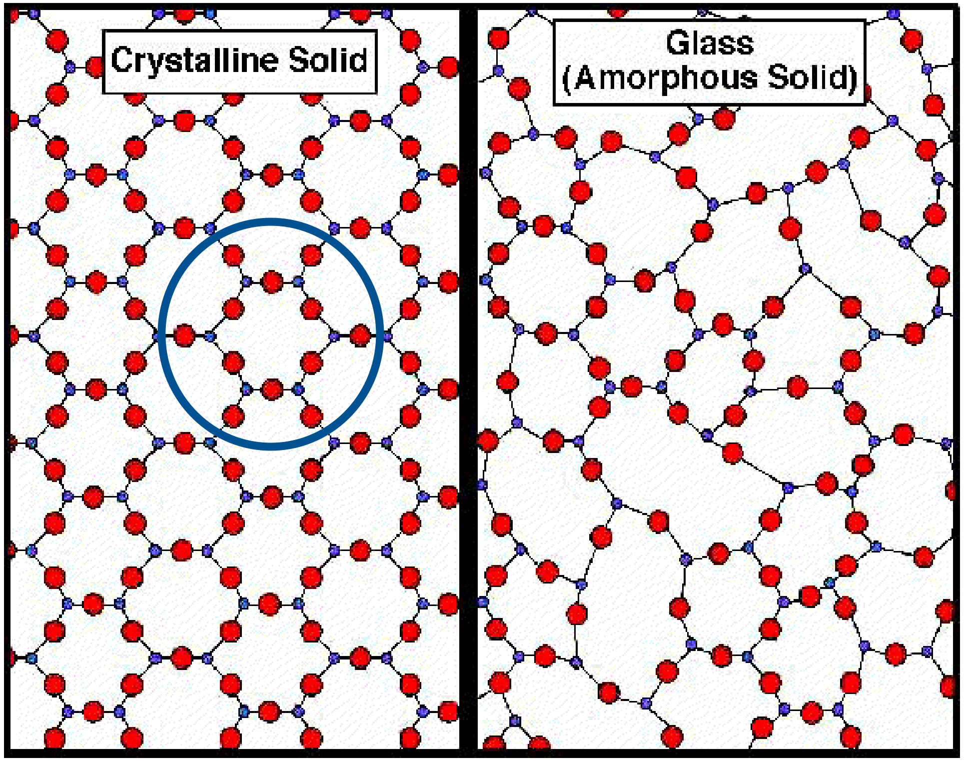
- Locally, atoms in glasses occupy sites that are similar to those in crystals, but…
- There is no direction in which you can move and find the same kind of atom in an identical site



Glasses are solids with local atomic arrangements like crystals, but lacking translational symmetry.

Structure changes cause differences in many properties

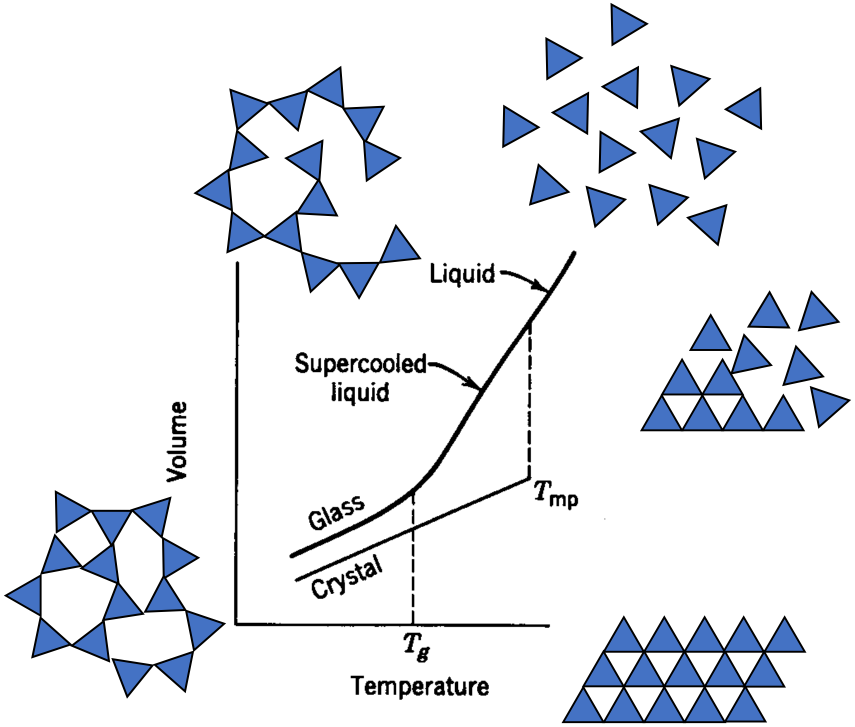
	Quartz (Crystalline)	Fused Silica (Amorphous)
Density (g/cc)	2.648	2.2
Modulus (GPa)	97.2 (para*) 76.5 (perp*)	73
CTE (ppm/^{o}C)	7.1 (para*) 13.2 (perp*)	0.5
Melting T (^{o}C)	1710	Soft at 1627



Para = parallel to C axis; Perp = perpendicular to C axis

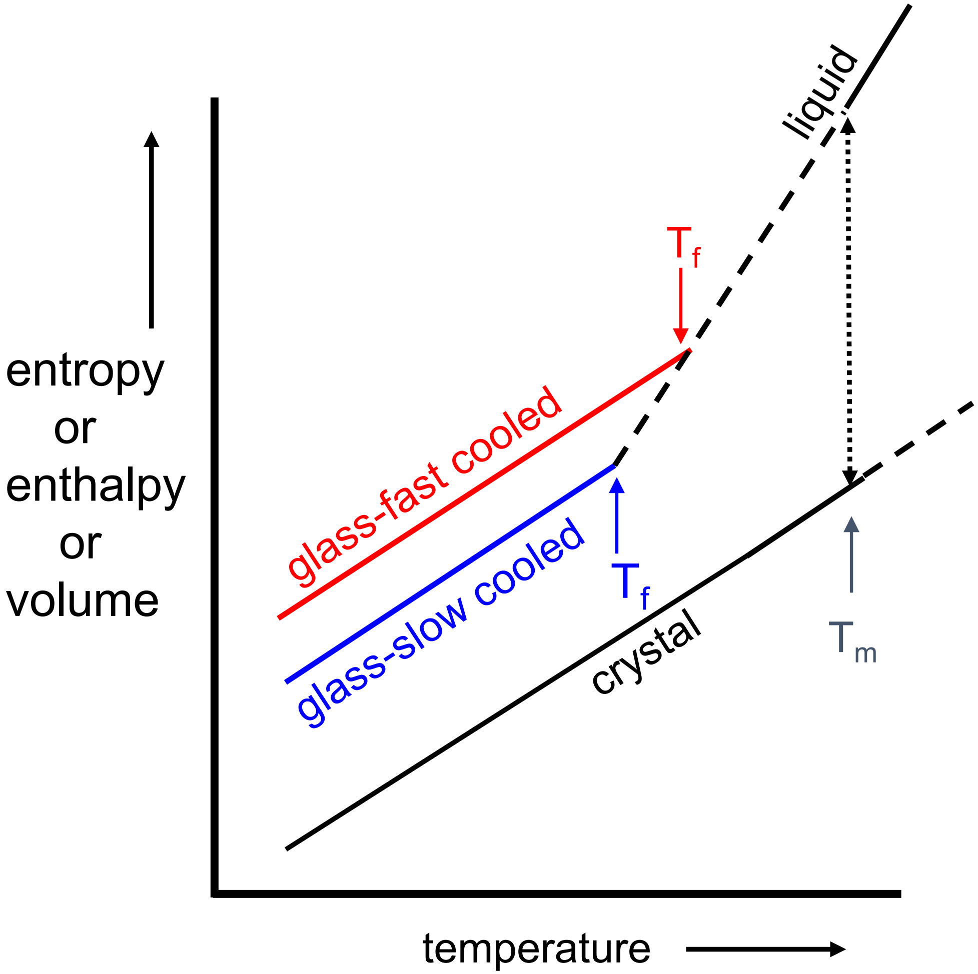
Glass' amorphous structure occurs as it is cooled from the molten state

- A liquid at a temperature below its freezing point is called a "supercooled" liquid. It's structure is "amorphous".
- If cooled rapidly enough, the liquid forms a glass. Its structure remains amorphous
- Glass has no melting and freezing point. It has a glass transition.
- Its properties vary with thermal history



Volume-Temperature diagram

How does glass differ from crystals from a thermal dynamic point of view?



Poise	Description
$\eta \sim 10^2$ Poise	Temperature required to get a homogeneous melt
$\eta = 10^4$ Poise	Working point (pressing, blowing, gob forming)
$\eta = 10^{7.6}$ Poise	Softening Point (glass deforms visibly under its own weight)
$\eta = 10^{13.18}$ Poise	Annealing Point (stresses are relieved in several minutes)
$\eta = 10^{14.7}$ Poise	Strain Point (stresses are relieved in several hours)

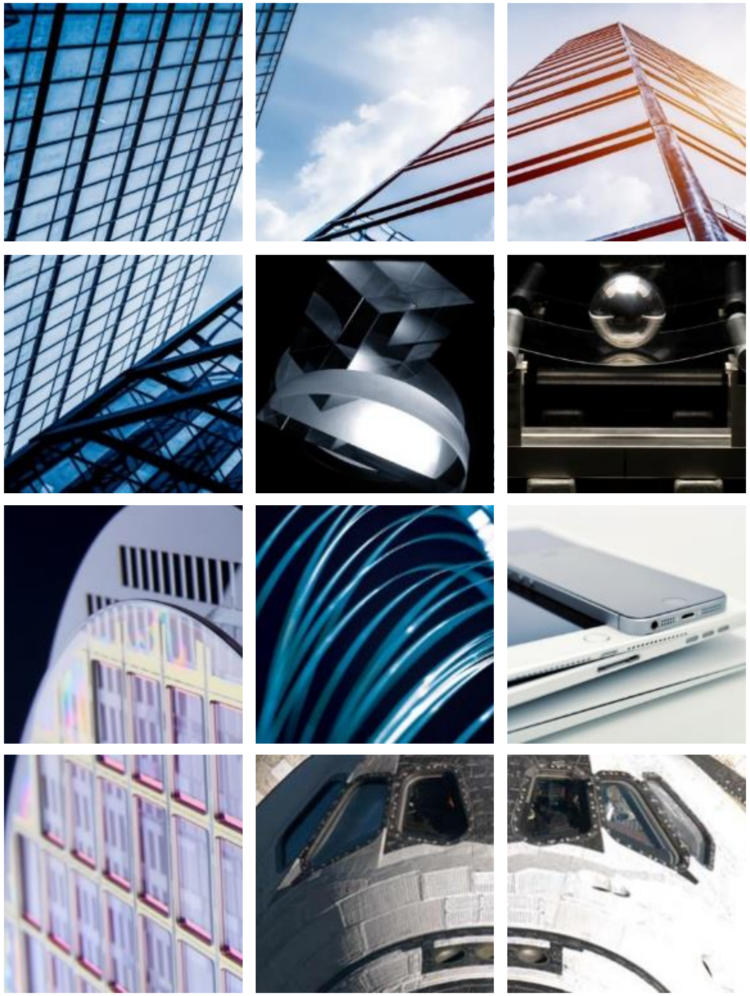
Overview of Glass Attributes

Common glass myths

1. Glass is glass. All glasses are the same.

2. Glass is weak.

3. Glass can contaminate semiconductor device fabrication.



Myth #1: Glass is glass

- Theoretically, any inorganic material can be made into glass (if you cool fast enough): e.g. oxide glasses, metallic glasses, chalcogenide glasses etc.

- Some common glasses:
  - High Purity Fused Silica (Corning HPFS®): Optical fiber
  - Alkali-free silicate glasses: Semiconductor, LCD
  - Borosilicate glass: Labware
  - Alkali silicate glasses: Corning® Gorilla® glass
  - Soda lime glass: Window

Soda-Lime-Silica Glass: Application and properties

Architectural Glass

Light Bulb Envelopes

Bottles & Containers

- First commercial glass
  - Abundant raw materials supply (silica sand, soda ash, limestone, feldspar)
  - Could be melted using wood fires

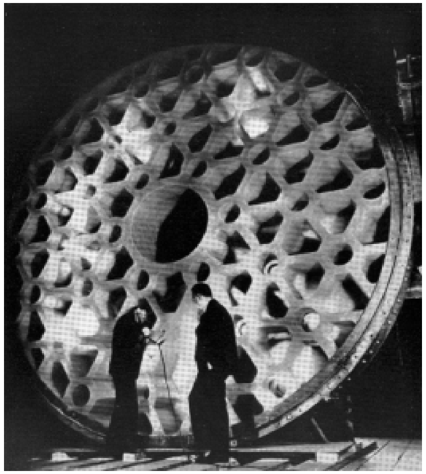
- Makes up the greatest volume of glass manufactured today

Typical properties of soda-lime silicate glass.

	Property	Units	Value
General	Density	g/cm^3	2.5
Mechanical	Young's Modulus	GPa	70
Thermal	Max. Use Temperature	°C	<500
	Thermal Conductivity	W/m.K	0.8
	Co-Efficient of Linear Expansion	10^{-6}/°C	9.1

Low cost manufacturing and stable composition

Borosilicate Glasses: Application and properties



200” Mt. Palomar Telescope Mirror

Optical Glass

Laboratory Ware

PYREX® Baking Ware 1915

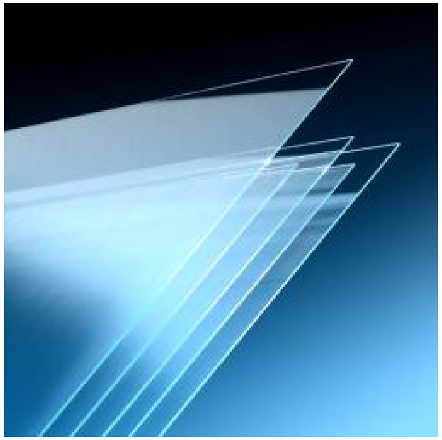
- Specialized glass composition for high thermal conduction, thermal shock and low thermal expansion

Typical properties of borosilicate glass.

	Property	Units	Value
General	Density	g/cm^3	2.23
Mechanical	Young's Modulus	GPa	64
Thermal	Max. Use Temperature	°C	500
	Thermal Conductivity	W/m.K	1.14
	Co-Efficient of Linear Expansion	10^{-6}/°C	3.3

High thermal conductivity and low thermal expansion applications

Aluminosilicate Glasses: Application and properties



LCD Substrate Glass

Reinforcing Fiberglass

Durable Cover Glass

- Highly designed glass composition with properties to exactly match application
- Special melting and forming process to attain the final sheet or other form factor attributes

Properties of Corning Eagle XG® glass.

	Property	Units	Value
General	Density	g/cm^3	2.38
Mechanical	Young's Modulus	GPa	73.6
Thermal	Max. Use Temperature	°C	~800
	Thermal Conductivity	W/m.K	1.09
	Co-Efficient of Linear Expansion	10^{-6}/°C	3.17

High strength and moderately high temperature applications

Fused Silica: Application and properties

Optical Elements

Hubble Telescope

The Space Shuttle

- High purity to attain specialized properties
- Special melting and forming process to maintain high purity

Properties of Corning HPFS ® glass.

	Property	Units	Value
General	Density	g/cm^3	2.2
Mechanical	Young's Modulus	GPa	73
Thermal	Max. Use Temperature	°C	~1200
	Thermal Conductivity	W/m.K	1.38
	Co-Efficient of Linear Expansion	10^{-6}/°C	0.57

High temperature and low thermal expansion applications

Myth #2: Glass is weak

- People feel that glass is weak, but…
  - The Space Shuttle's windows are glass
  - Skyscrapers are covered by glass
  - Optical cable can be spooled and used as submarine cable for long distances
  - Windshield protection from bullets
  - Cover glass helps protect panel displays

The intrinsic strength of glass is based upon Si-O-Si network strength, but in practice, it is much lower

- Theoretical
  - ~ 2,000 - 4,000 kpsi (14 - 30 GPa)
- Typical
  - Bulk glass: ~2 - 20 kpsi (0.014 - 0.14 GPa)
  - Optical fiber: ~ 100 - 2,000 kpsi (0.7 - 14 GPa)

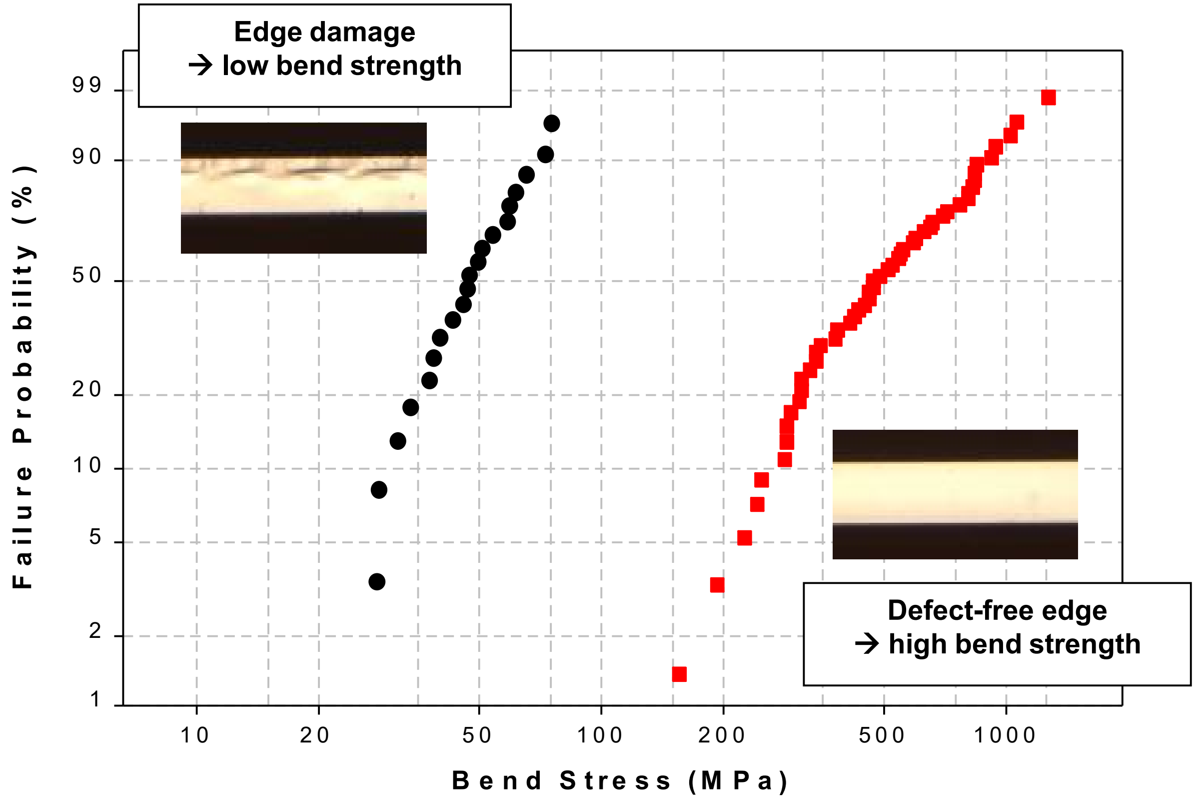
Why does glass break?

Failure occurs as a result of *crack propagation*[1] by the localization of *tensile stress*[2] at a *defect*[3] or *flaw* on the glass surface, such as a *crack*

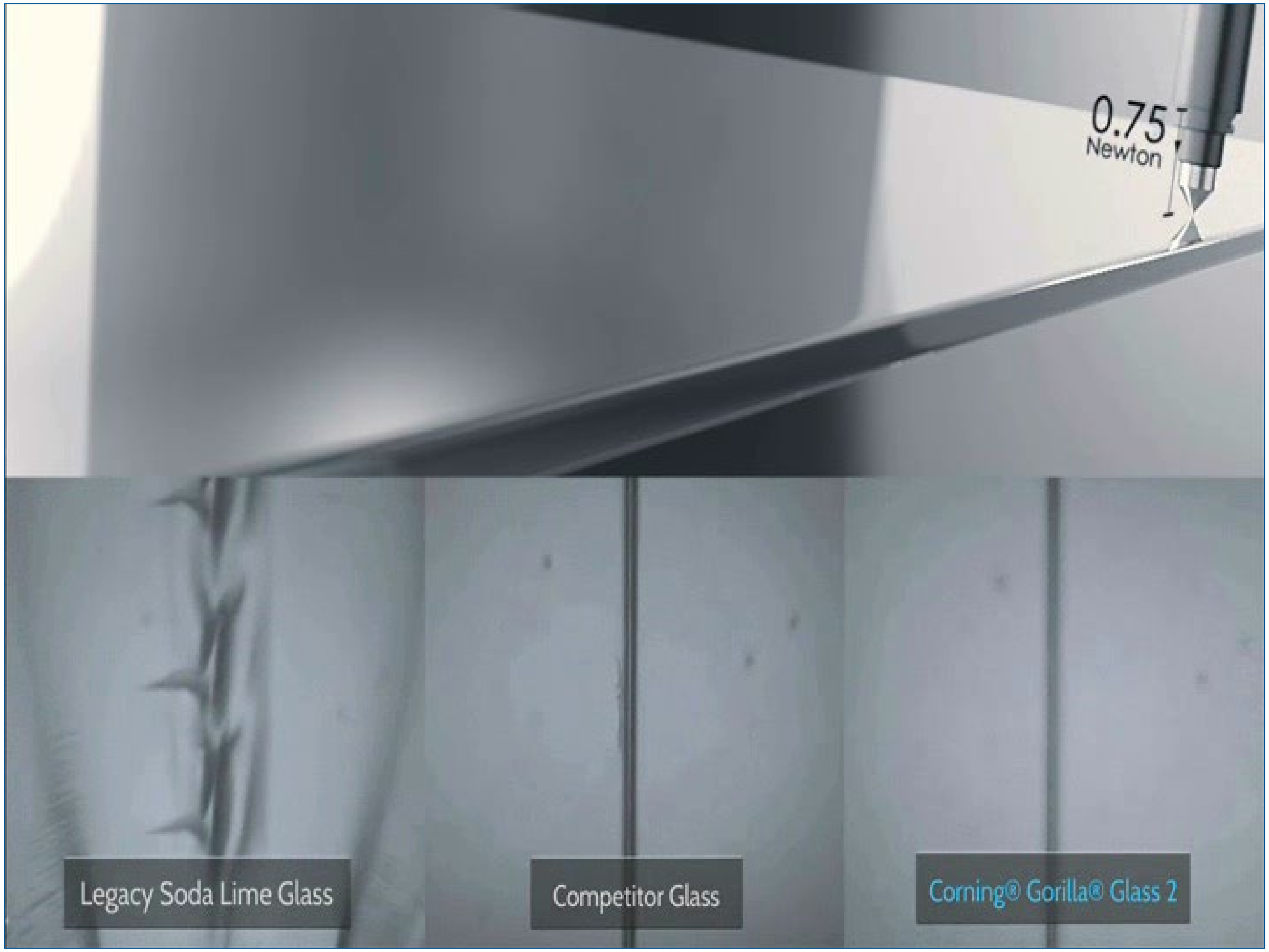
Key: [1]Phenomenon, [2]cause, [3]cause

Ultra-slim glass is very strong when made properly and handled appropriately

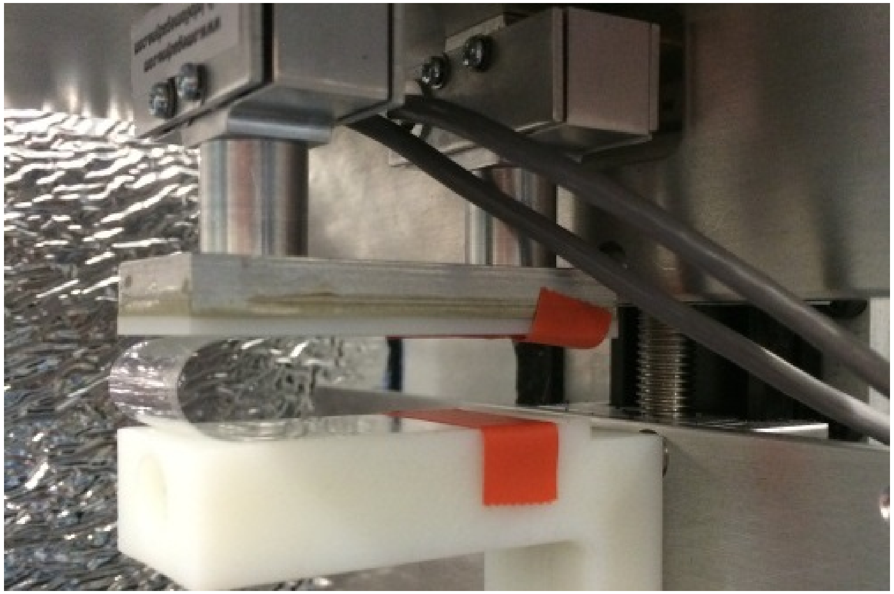
- Glass breaks when flaw size & stress reach threshold
- Preventing flaws and stress is key to glass reliability



Strength is not a given. It needs to be engineered into the glass.

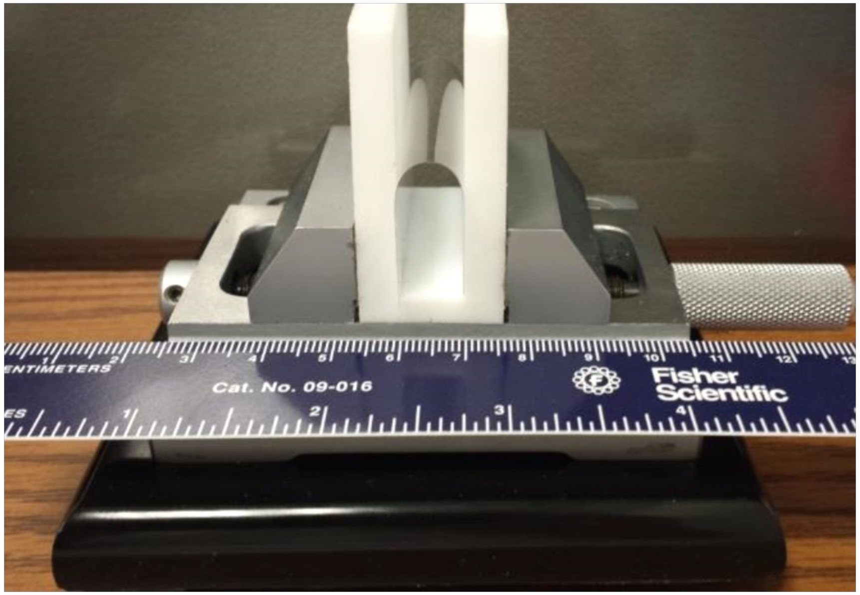


This is glass, not plastic…



Dynamic 2PB cyclical testing between R = 5 mm and R = 10 mm

- Testing conducted at 25C and 50% RH.
- Achieves >200,000 cycles routinely.
- Tests taken up to 1,000,000 cycles with part survival



Static test of 10 mm plate separation

- Specimens still intact since 2/27/14

Ion-exchangeable 75 micron glass can be bent repeatedly

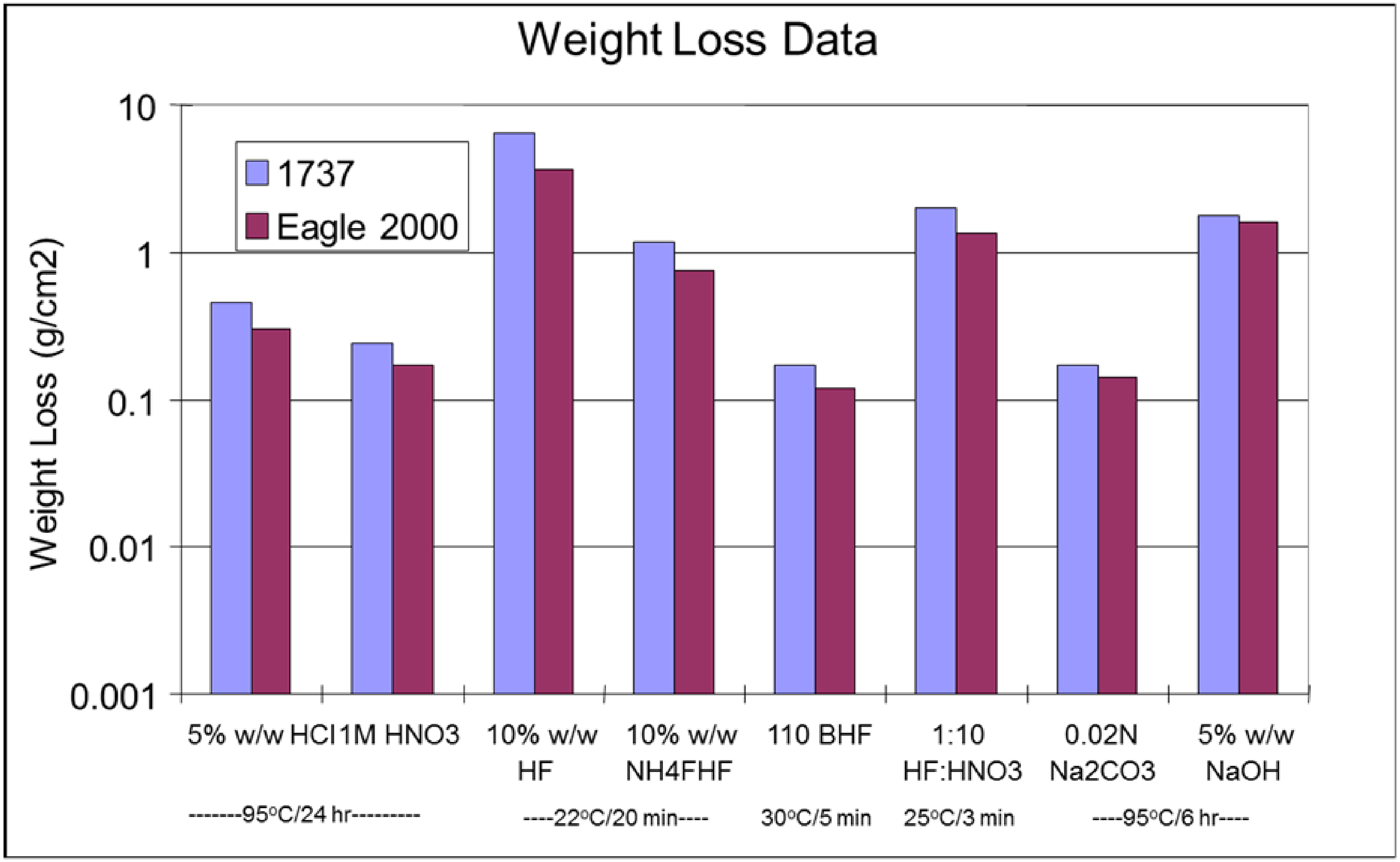
Myth #3: Glass can contaminate semiconductor device fabrication

- Not all the glass contains alkali elements (Li, Na, K …)
  - Fused silica (SiO_2)
  - Ultra low expansion glass (SiO_2-TiO_2)
  - OLED (organic light-emitting diode), LTPS (low temperature polysilicon) - LCD display glass (alkaline earth aluminosilicate)

- *Glass compositions can be designed to fit applications*

Glass can be designed with improved attributes

Example: Improved chemical durability in LCD substrates



Quiz

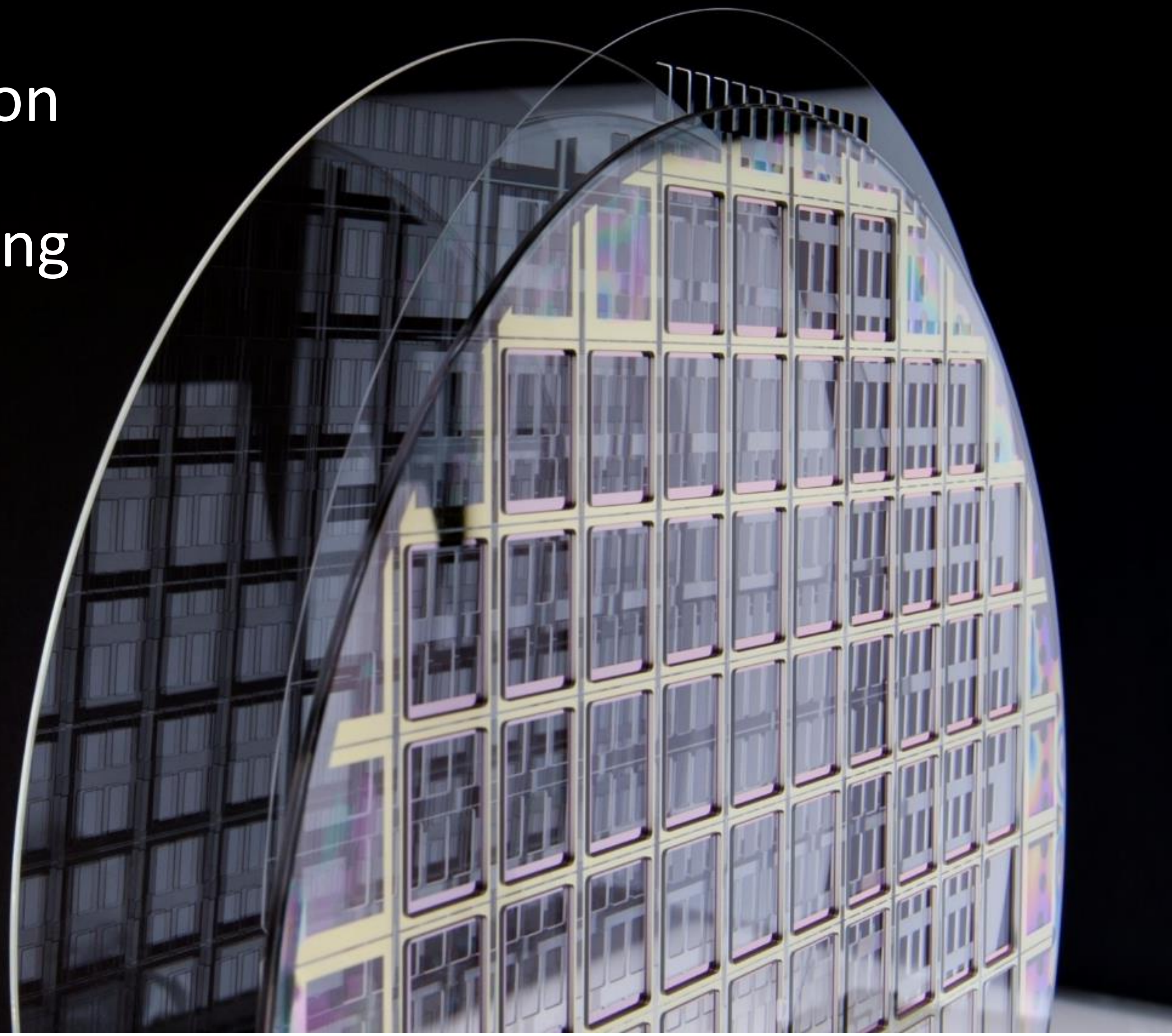
1. Which has a higher volume, the glass or crystalline phase of the same chemical formula?

2. Which type of glass is used for laboratory ware, optical glass, and PYREX?

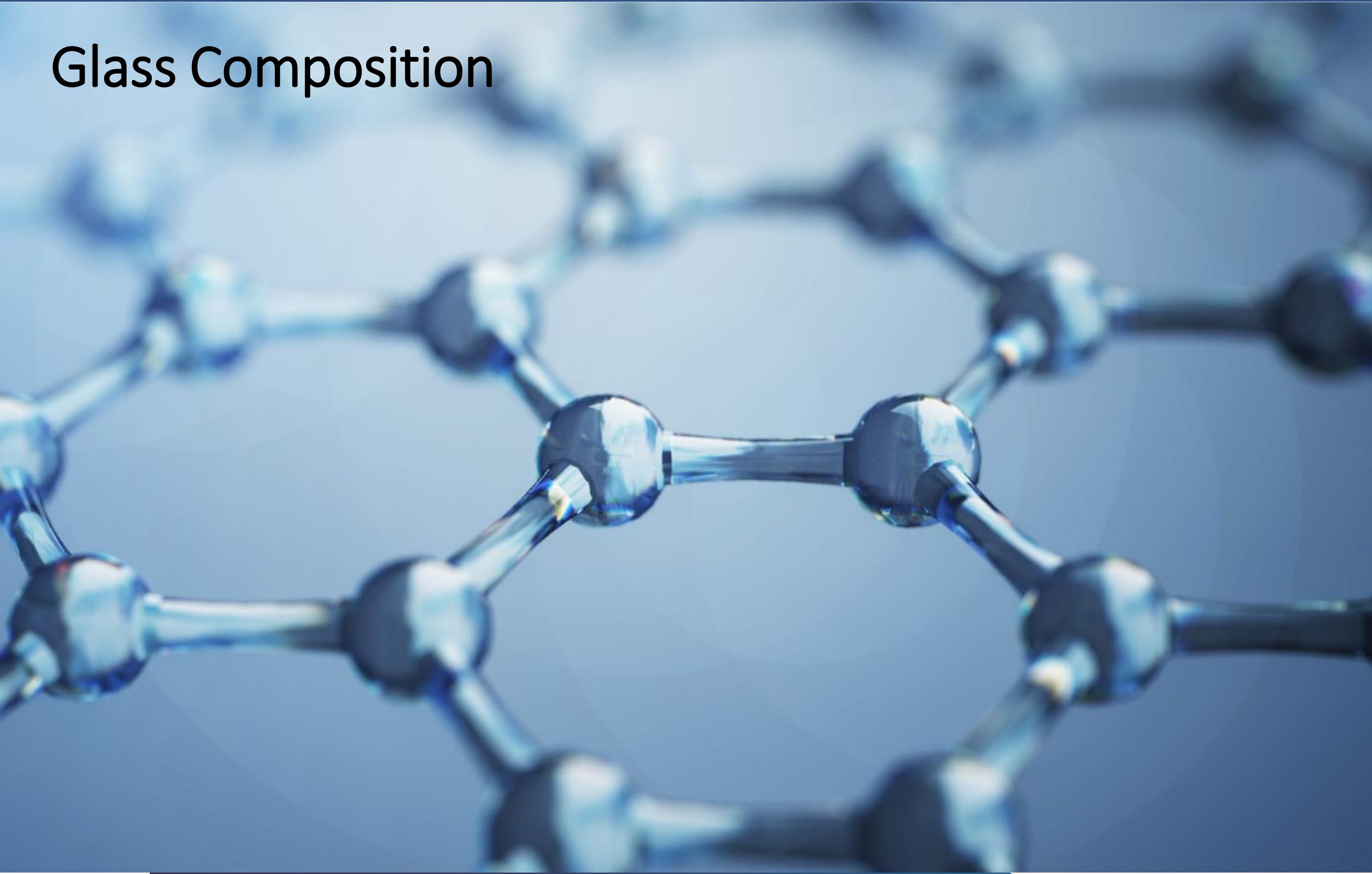
3. What type of elements are removed from glass to make it a good semiconductor composition?

2. Glass Properties and Manufacturing

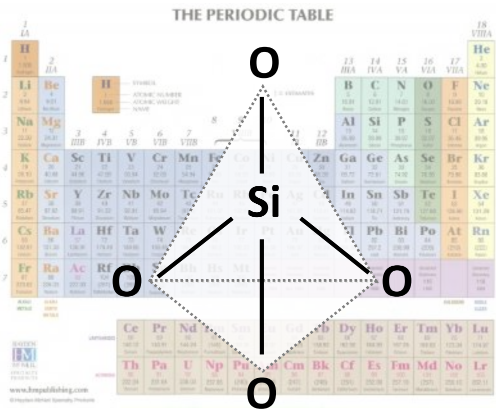
- Glass Composition
- Melting & Forming Processes
- Secondary Processes
- Glass Handling



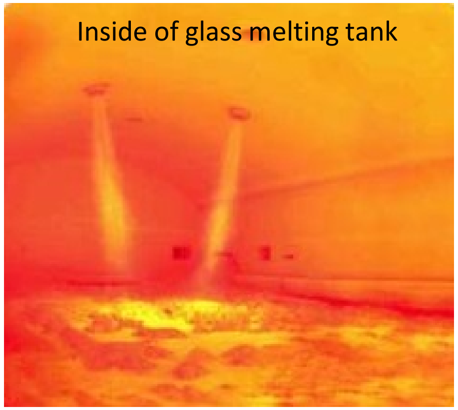
Glass Composition



Composition dictates glass properties
Options, options, options…



Glass Composition design to Optimized Properties and Manufacturability



Manufacturing Process

Secondary Process Steps

How does glass differ from silicon?

Glass composition is tunable, therefore the properties vary across a wide range

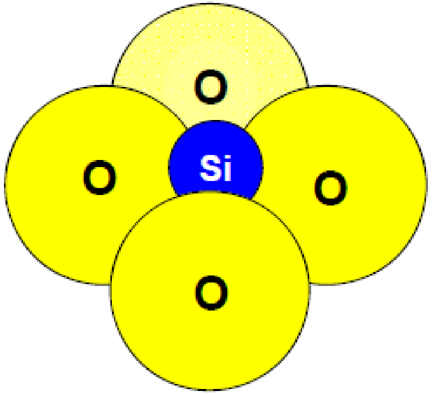
	Low	High	Si [100]
Density (g/cc)	2.2	3.21	2.33
CTE (ppm/ºC) (0-300 ºC)	0	13	3.0
Elastic Modulus (GPa)	60	150	141
Vickers hardness (200 g)	450	700	1015
Dielectric Constant (1 kHz)	3.8	12	11.9

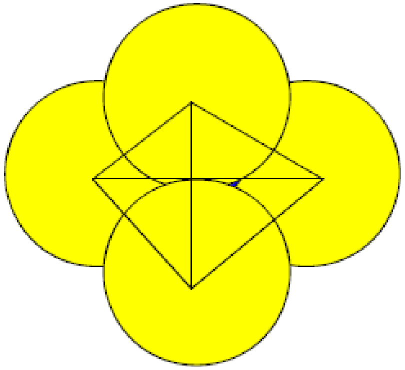
Silicate glass

- The backbone of most commercial glass you've ever encountered is ***SiO_2***, or ***silica***. This is why they are called ***silicate glasses***.
  - In pure SiO_2, every silicon (Si) atom bonds to four oxygen atoms, and every oxygen bonds to 2 Si atoms:

$$SiO_{4/2} = SiO_2$$

  - The four oxygen define a regular tetrahedron with Si in the center





Building SiO_2 glass (cont'd)

- These $SiO_{4/2}$ tetrahedra share corners
  - Since a tetrahedron is a 3 dimensional object, these linkages extend in three dimensions
- This results in a three dimensional ***network*** of linked $SiO_{4/2}$ tetrahedra
- Other oxides that forms 2D and 3D networks are GeO_2, P_2O_5 and B_2O_3
- These oxides (SiO_2, GeO_2, P_2O_5 and B_2O_3 often called ***network formers***

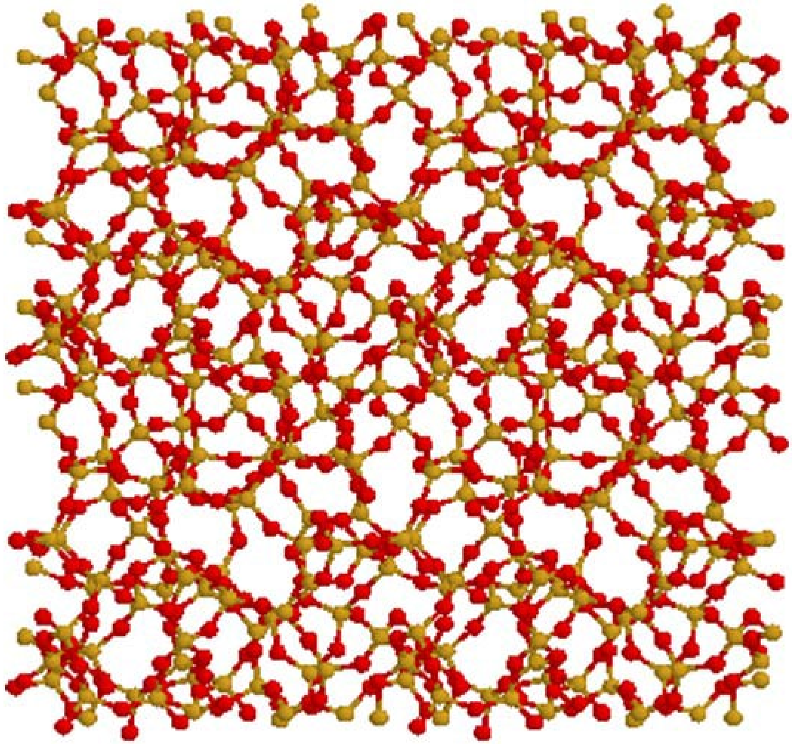


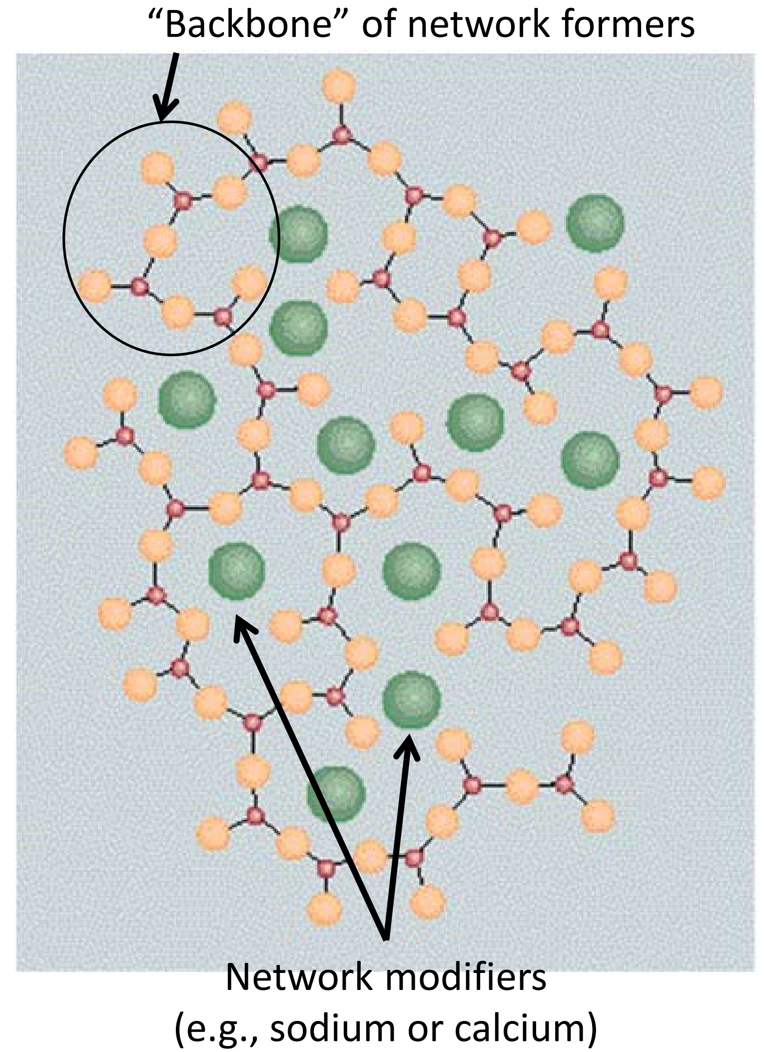
Image source: www.research.ibm.com/amorphous

What about atoms besides network formers?

- If you add elements like sodium to SiO_2, Si-O-Si linkages are broken, and MO-Si bonds form:

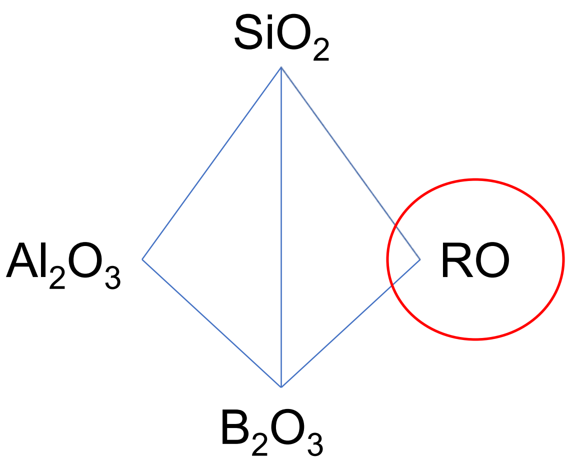
  Si-O-Si + M-O-M = 2M-O-Si

- If M bonds to a bunch of oxygen, then the network structure breaks down.
- Elements that have low ionic charge (+1 or +2) and high numbers of bonds (4 or more are called ***network modifiers***
- Alkali oxides (Li_2O, Na_2O, K_2O) and alkaline-earth oxides (MgO, CaO, SrO) are examples of network modifiers.



"In the midst of difficulty lies opportunity"

- Glass is a tremendously complex science
  - Multidimensional problem of glass composition
  - Complex interplay of physical properties



CaO, MgO, BaO, SrO

- This complexity gives glass its versatility
  - Many variables = many options!

The periodic table…

THE PERIODIC TABLE

Key: H = SYMBOL; 1 = ATOMIC NUMBER; 1.008 = ATOMIC WEIGHT; Hydrogen = NAME

( ) = ESTIMATES

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	H 1 1.008 Hydrogen																	He 2 4.00 Helium
2	Li 3 6.94 Lithium	Be 4 9.01 Beryllium											B 5 10.81 Boron	C 6 12.01 Carbon	N 7 14.01 Nitrogen	O 8 16.00 Oxygen	F 9 19.00 Fluorine	Ne 10 20.18 Neon
3	Na 11 22.99 Sodium	Mg 12 24.31 Magnesium											Al 13 26.98 Aluminum	Si 14 28.09 Silicon	P 15 30.97 Phosphorus	S 16 32.07 Sulfur	Cl 17 35.45 Chlorine	Ar 18 39.95 Argon
4	K 19 39.10 Potassium	Ca 20 40.08 Calcium	Sc 21 44.96 Scandium	Ti 22 47.88 Titanium	V 23 50.94 Vanadium	Cr 24 52.00 Chromium	Mn 25 54.94 Manganese	Fe 26 55.85 Iron	Co 27 58.93 Cobalt	Ni 28 58.69 Nickel	Cu 29 63.55 Copper	Zn 30 65.39 Zinc	Ga 31 69.72 Gallium	Ge 32 72.61 Germanium	As 33 74.92 Arsenic	Se 34 78.96 Selenium	Br 35 79.90 Bromine	Kr 36 83.80 Krypton
5	Rb 37 85.47 Rubidium	Sr 38 87.62 Strontium	Y 39 88.91 Yttrium	Zr 40 91.22 Zirconium	Nb 41 92.91 Niobium	Mo 42 95.94 Molybdenum	Tc 43 (97.9) Technetium	Ru 44 101.07 Ruthenium	Rh 45 102.91 Rhodium	Pd 46 106.42 Palladium	Ag 47 107.87 Silver	Cd 48 112.41 Cadmium	In 49 114.82 Indium	Sn 50 118.71 Tin	Sb 51 121.76 Antimony	Te 52 127.60 Tellurium	I 53 126.90 Iodine	Xe 54 131.29 Xenon
6	Cs 55 132.91 Cesium	Ba 56 137.33 Barium	La 57 138.91 Lanthanum	Hf 72 178.49 Hafnium	Ta 73 180.95 Tantalum	W 74 183.85 Tungsten	Re 75 186.21 Rhenium	Os 76 190.2 Osmium	Ir 77 192.22 Iridium	Pt 78 195.08 Platinum	Au 79 196.97 Gold	Hg 80 200.59 Mercury	Tl 81 204.38 Thallium	Pb 82 207.2 Lead	Bi 83 208.98 Bismuth	Po 84 (209) Polonium	At 85 (210) Astatine	Rn 86 (222) Radon
7	Fr 87 223.02 Francium	Ra 88 226.03 Radium	Ac 89 227.03 Actinium	Rf 104 (261) Rutherfordium	Db 105 (262) Dubnium	Sg 106 (263) Seaborgium	Bh 107 (262) Bohrium	Hs 108 (265) Hassium	Mt 109 (266) Meitnerium	Unnamed Discovery 110 Nov. 1994	Unnamed Discovery 111 Nov. 1994	Unnamed Discovery 112 1996		Unnamed Discovery 114 1999		Unnamed Discovery 116 1999		Unnamed Discovery 118 1999
	ALKALI METALS	ALKALI EARTH METALS															HALOGENS	NOBLE GASES

LANTHANIDES	Ce 58 140.12 Cerium	Pr 59 140.91 Praseodymium	Nd 60 144.24 Neodymium	Pm 61 (145) Promethium	Sm 62 150.36 Samarium	Eu 63 152.97 Europium	Gd 64 157.25 Gadolinium	Tb 65 158.93 Terbium	Dy 66 162.50 Dysprosium	Ho 67 164.93 Holmium	Er 68 167.26 Erbium	Tm 69 168.93 Thulium	Yb 70 173.04 Ytterbium	Lu 71 174.97 Lutetium
ACTINIDES	Th 90 232.04 Thorium	Pa 91 231.04 Protactinium	U 92 238.03 Uranium	Np 93 237.05 Neptunium	Pu 94 (240) Plutonium	Am 95 243.06 Americium	Cm 96 (247) Curium	Bk 97 (248) Berkelium	Cf 98 (251) Californium	Es 99 252.08 Einsteinium	Fm 100 257.10 Fermium	Md 101 (257) Mendelevium	No 102 259.10 Nobelium	Lr 103 262.11 Lawrencium

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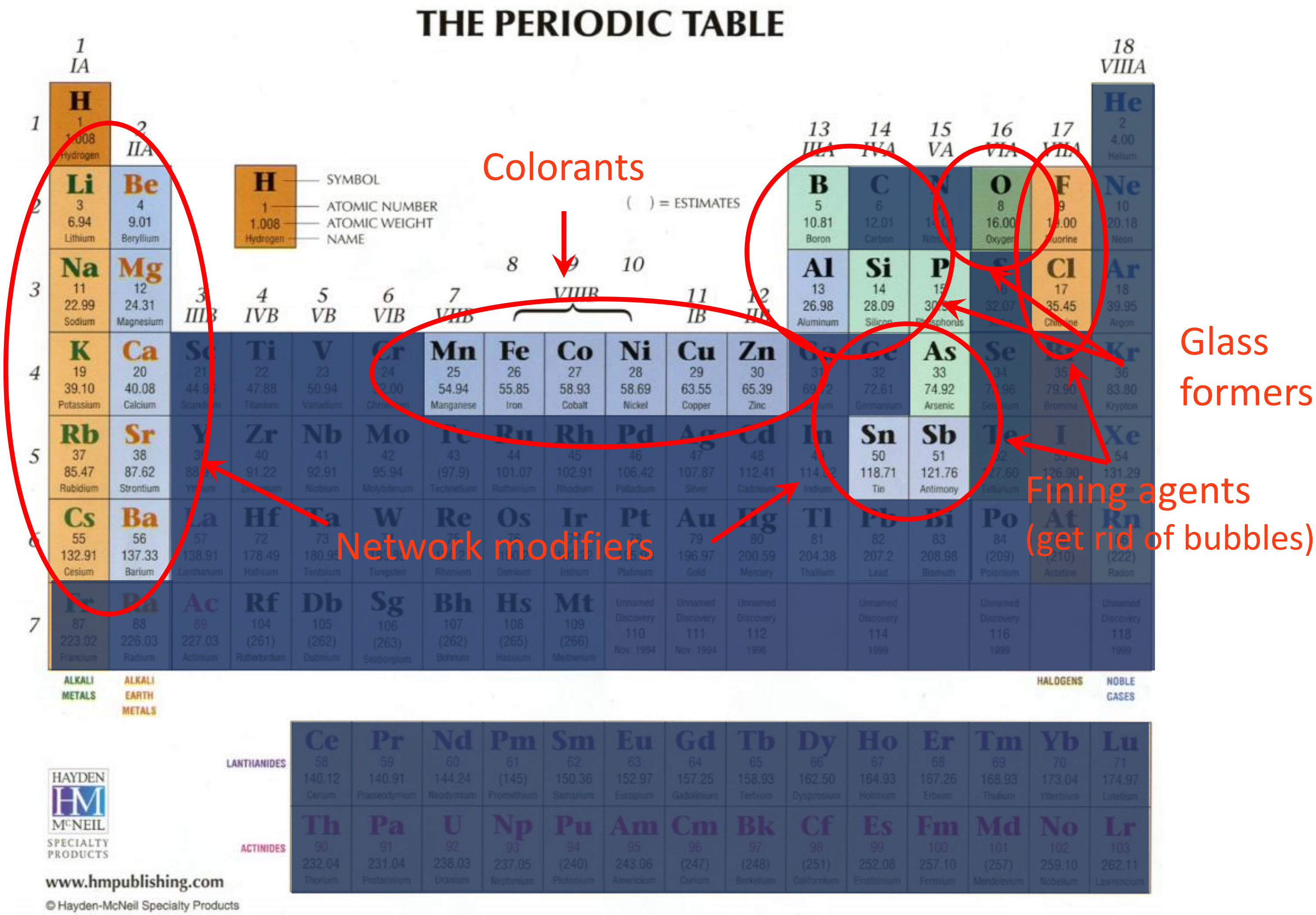
…The commercial glass chemist's periodic table



These components determine properties of glass

Component	Role	Expansion	Density	Modulus	Hardness	Durability	Transmission
SiO_2	NF	-	-	-	-	+	
Al_2O_3	NF	-	+	+	+	+	
B_2O_3	NF	-	-	-	-	+	
Li_2O	M	+		-	-	-	
Na_2O	M	+		-	-	-	
K_2O	M	+	+	-	-	-	
MgO	M			+	+	+	
CaO	M			+	+	+	
TiO_2	C		+	+	+	+	-
ZrO_2	NF/M		+	+	+	+	
Sb_2O_3	F	+	+	-	-	+	
SnO_2	F			+	+	+	

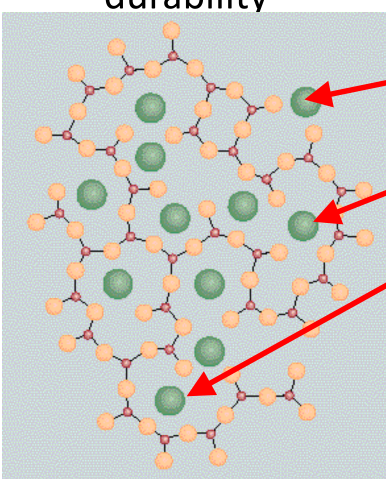
Key
+ = Component increases this property
- = Component decreases this property
 = Component has little effect on this property

NF: Network Former
M: Modifier
C: Colorant
F: Finer

Glass scientists tailor chemical compositions to customers requirements

What is soda lime glass?

1. We start with sand (basically SiO_2), but it is waaaaaay too hard to melt. Iron is for free.
2. We add what we call a flux (Na_2O) to improve melting.
   - Naturally occurring sources of Na_2O always contain K_2O
   - Makes for a glass with wretched durability
3. O with CaO to lity.
   - MgO
4. o suppress



Oxide	Percent by weight
SiO_2	99.7
Al_2O_3	0.14
Na_2O	18.7
K2O	1.2
CaO	
MgO	
Fe_2O_3	0.1

What is soda lime glass?

Glass component	Function	Oxide	Percent by weight
Sand	Network former	SiO_2	69.3
		Al_2O_3	3.1
Flux	Change melting; improve processability	Na_2O	15.8
		K_2O	0.7
Lime	Improve durability	CaO	10.7
		MgO	0.3
Sand	Impurity	Fe_2O_3	0.07

That's great, but what if I don't want a window?

- LCD industry needed a substrate with specific attributes:
  - Alkali-free (to avoid poisoning TFT)
  - Dimensionally stable (to allow proper registry)
  - Clean, flat surface (to avoid discontinuities in films)
- Traditional "glass" wouldn't work
  - Soda lime glass has soda (Na)
  - Dimensional stability was poor
  - Surface quality was insufficient
- Industry developed "display glasses" as a category
  - Alkali free
    - Have to add other network modifiers
  - High viscosity glasses (high dimensional stability)
    - Requires other network formers
  - Ultra flat and clean sheets
    - Careful attention to melting/forming (later in the course)

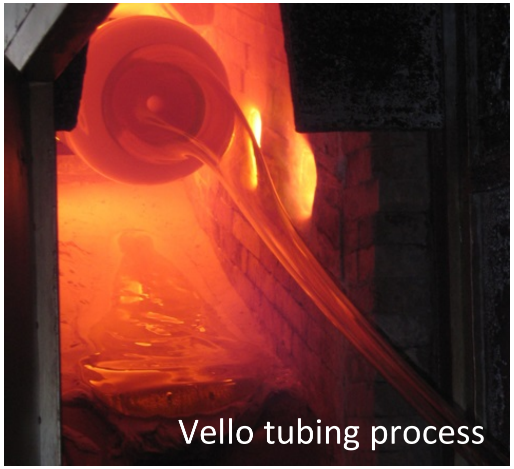
Glass properties and manufacturing

- Glass Composition
- **Melting & Forming Processes**
- Secondary Processes
- Glass Handling

Forming in 1D

- Fiber: A solid rod or stream of glass drawn into a narrow cylinder
  - Used in telecom (optical fiber), architecture and insulation (fiberglass), lighting

- Tubing: basically fiber or rod with a hole in the middle, used in fluid and gas transport at all dimensions, from microns to decimeters


Vello tubing process

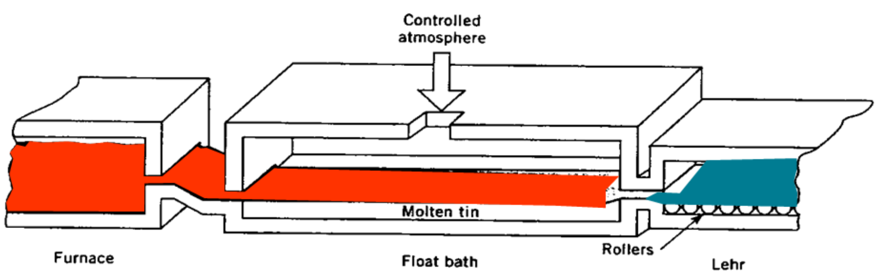
Forming in 2D: Float process
Typical for soda lime glass

- Glass formed by floating on a bath of molten tin

- Advantages
  - Economy of scale - several hundred tons per day per float line for architectural and automotive applications.
  - Cheaper than plate glass with equal or better flatness and surface quality

- Disadvantages
  - Constant fight to keep the tin in the batch
  - Requires reducing atmosphere (restricts glass choices)
  - Requires polishing for high performance applications

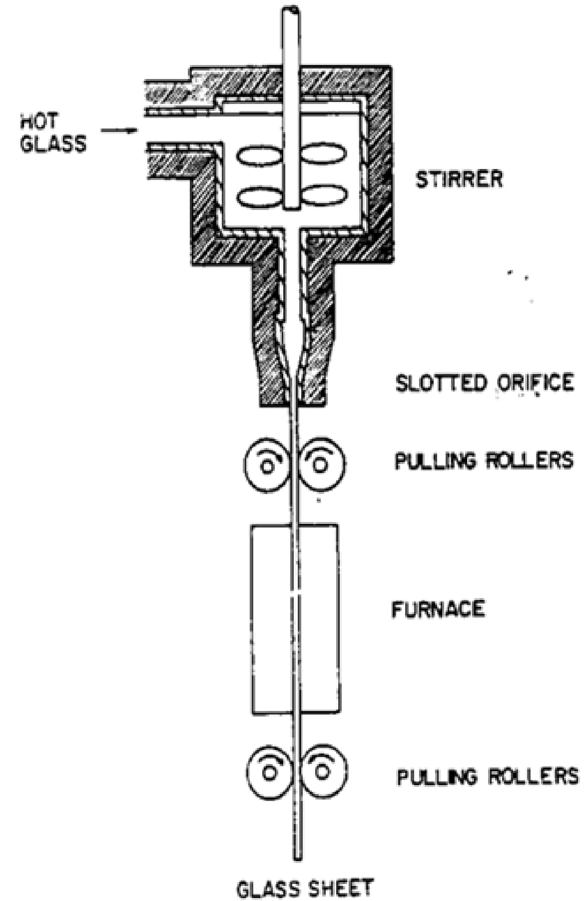
Diagram of the Float Glass Process



Forming in 2D: Slot Draw

- Glass is drawn downward from a refractory metal slot
- Thickness is defined by the slot dimensions, depth of molten glass above the slot (called "head"), viscosity at the slot, and draw speed
- Capable of very thin (<0.1 mm) sheet
- Surface quality is limited by slot condition (corrosion and erosion effects)

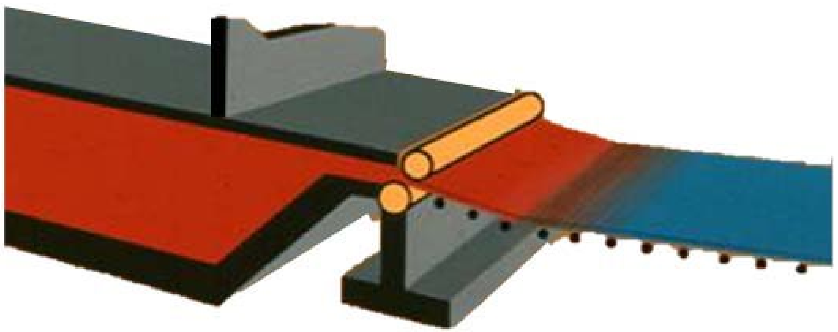
Diagram of the Slot Draw Process



Source: Diagram of the Slot-Draw Process, "Glasses for Flat Panel Displays," by W.H. Dumbaugh, P.L. Bocko and F.P. Fehlner, page 90 in High Performance Glasses, M. Cable and J.M. Parker (eds.), Blackie, London, 1992, pp. 86-101

Forming in 2D: Rolling

- Viscous melt rolled to desired thickness
- Rollers remove heat to solidify glass
- Glass cooled to rigid state on a series of supporting rollers
- Surface quality determined by roll surfaces

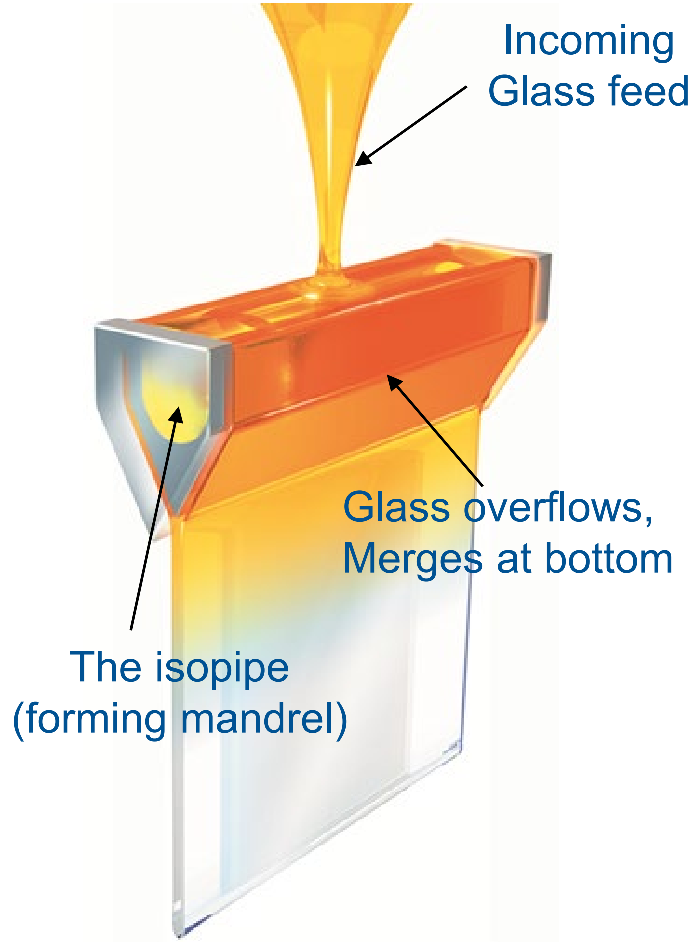


Forming in 2D: Display glass

- Glass can be pulled, stretched, or squeezed into wide (up to 11 feet!) sheets.
- Fusion draw delivers the best surface quality for Display glass.

  Fusion > Slot draw > Float > Rolling

- In many current markets, glass companies sell a surface with a bulk-glass support.



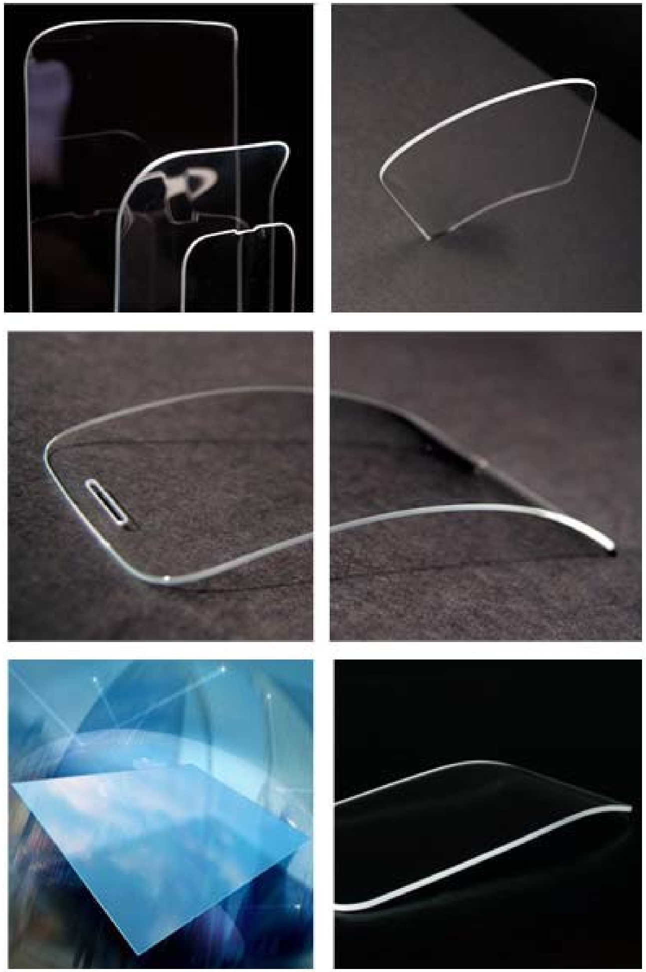
A schematic of fusion draw process

Forming in 2D: Fusion down draw

- "Pristine" surface
  - Enabled non-polished substrates for Thin Film Transistor fabrication that is the basis of the LCD process
- Ability to extend up past 3 meter
  - Enabled Gen 10 size
- Precise thickness control across the draw width
  - 0.1 – 3.0 mm demonstrated

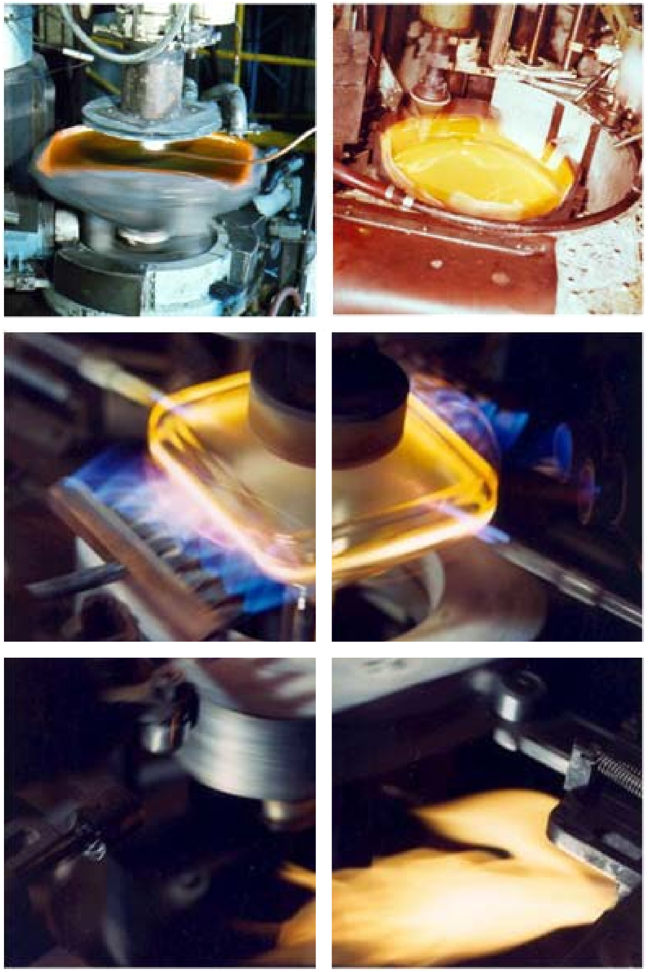
Forming in 3D

- By forcing a sheet into a third dimension, we create three dimensional objects
- Forming methods include: pressing, molding, stamping, sheet-coin, sagging, vacuum casting
- High tolerances generally require high viscosity, e.g., sagging is better than molding
- Subsequent steps can include cutting, trimming, grinding, polishing, etc.



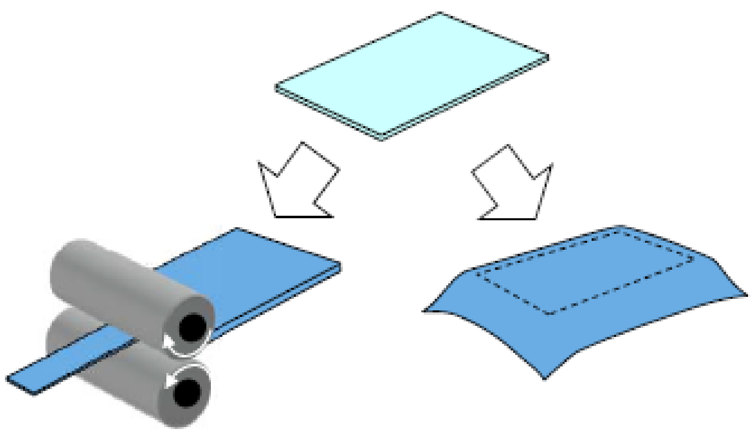
Forming in 3D: Mold / Cast

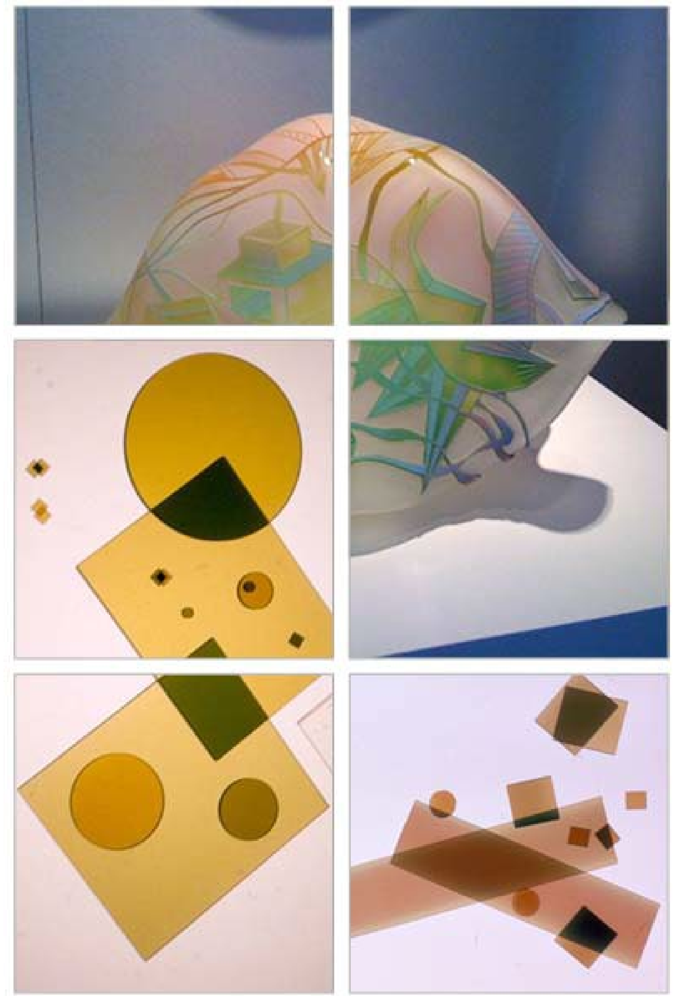
- Glass behaves as a “clay” or “plastic” at appropriate temperatures
- Able to make complicated 3D shapes repeatedly
  - Bulbs
  - Bottles
  - Cups
  - CRT front panels
  - CRT necks
  - Missile nose cones



Forming in 3D: Redraw / Reform

- Metal can deform plastically at room temperature
- Glass can deform visco-elastically at softening point





Glass Properties and Manufacturing

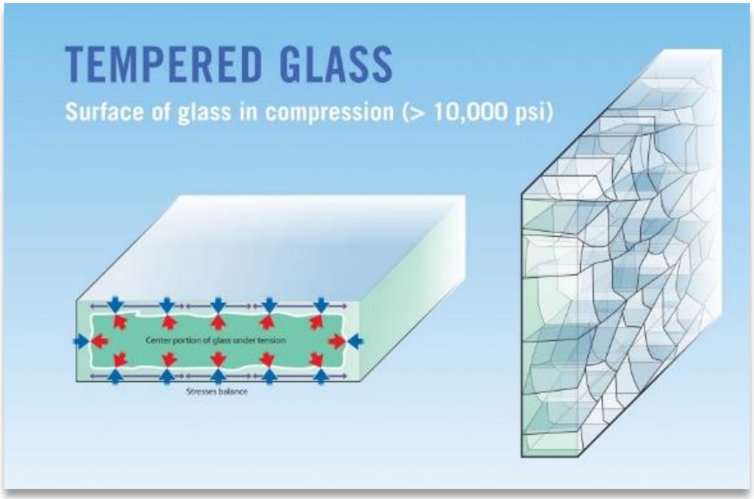
- Glass Composition
- Melting & Forming Process
- **Secondary Processes**
- Glass Handling

Examples of secondary processes

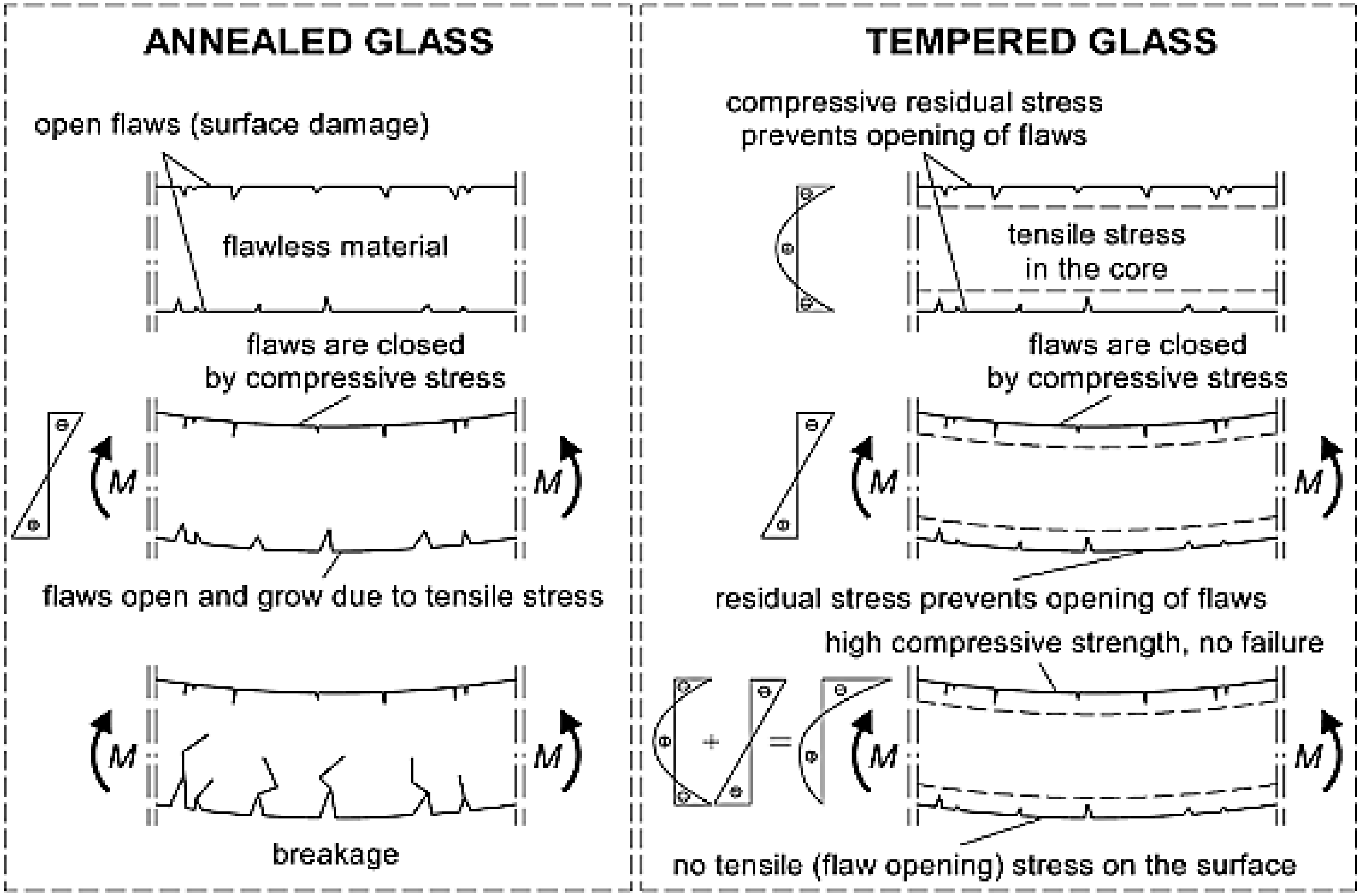
- **Tempering**
  - Thermal tempering
    - Rapidly cool a thick glass article to put surface in compression
    - Surface compression = strength
  - Chemical tempering (Ion Exchange)
    - Exchange in large mobile cat-ions for small mobile cat-ions, putting the surface in compression
    - LOTS of surface compression = LOTS of strength
- **Lamination**
  - Low CTE clad is put in compression
  - Surface compression = strength
- **Irradiation**
  - Photosensitive glasses can be masked and exposed to radiation
  - After exposure, a subsequent thermal cycle will cause crystals to grow in exposed region
  - Exposed region can be etched away

Thermal tempering of glass

- Thermally tempered glass articles have parabolic stress profiles (compression ~20-25% of thickness) produced using a rapid quench from near softening temperatures
- Employed in architectural and automotive applications for improved strength, toughness, thermal shock, and fatigue resistance
- When thermally tempered glass breaks it is highly frangible, producing relatively harmless “rock salt” like particles called “dicing”



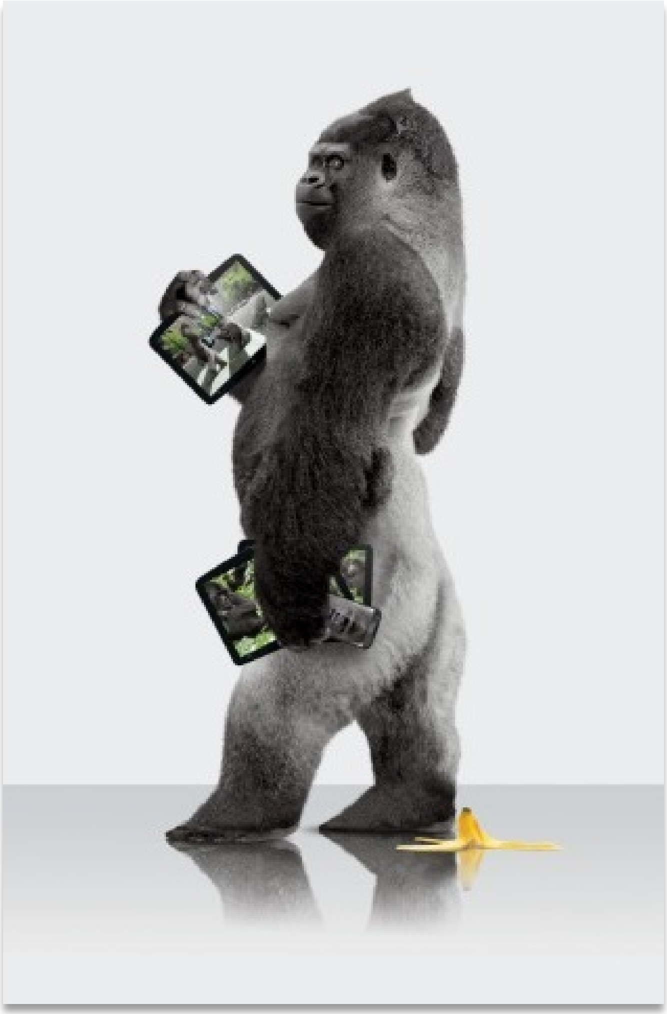
Thermal tempering of glass: How does it work?



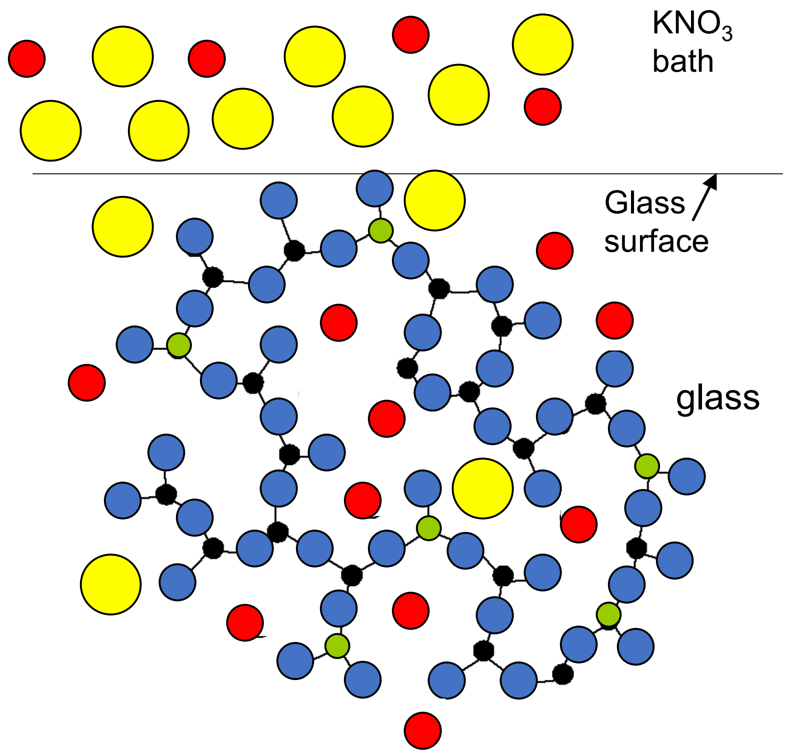
Ref. Structural Use of Glass, IABSE, 2009

Ion Exchange Process: Corning® Gorilla® Glass

- Glass similar to current Gorilla® Glass was developed by Ellen Mochel in the mid '60s
  - Target market then: Auto windshields
- Current Gorilla® Glass is uniquely designed for the fusion sheet glass manufacturing process
- Very high surface compressive stress, falling to zero through 40-60 microns results high resistance to damage
  - Example: Gorilla Glass forced through a bend that would fracture normal glass
  - Practical: It resists fracture due to blunt or sharp contact

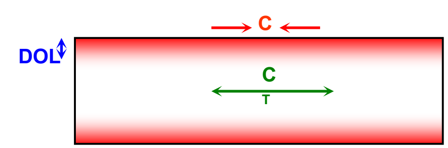


The ion-exchange process



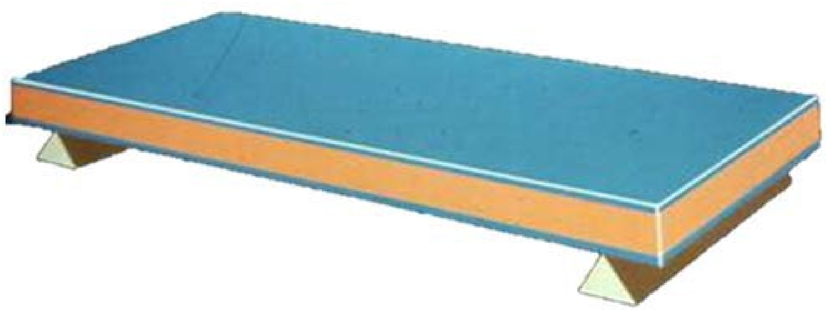
The incoming ion (K^+) and its larger volume produces:

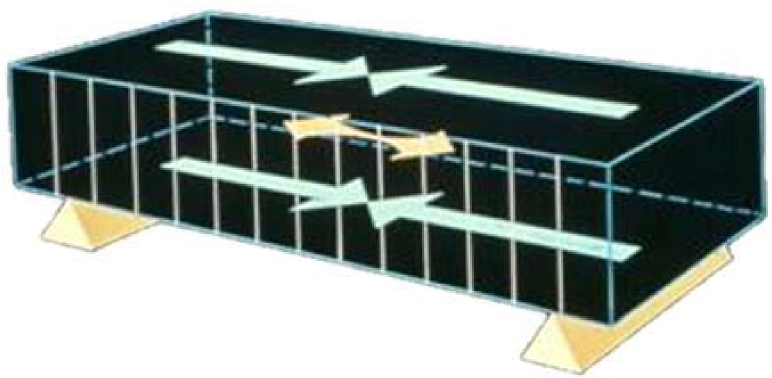
- Compressive stress on the surface
- Concentration distribution resulting in a stress profile



Glass-glass lamination

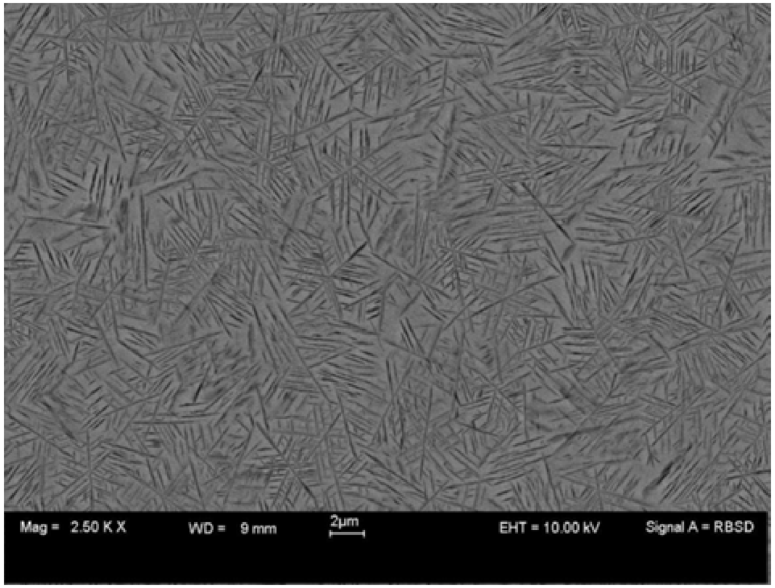
- Cladding glass has lower thermal expansion than core glass, therefore goes into compression when cooled from the forming temperatures

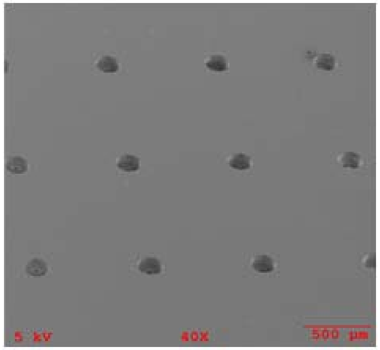


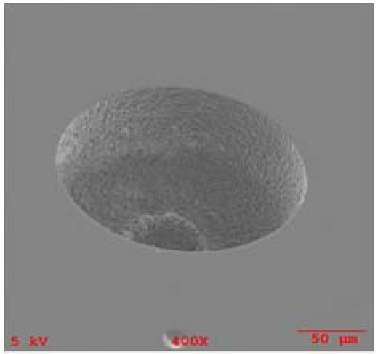


Photosensitive glass: Fotoform™

- Can mask glass to create patterns
  - Can be complex and/or very fine
- After heat treatment, exposed regions form crystals
- If done properly, crystals can form interlocking structure
- Interlocking structure can be preferentially etched away
  - Can make holes, channels, etc.





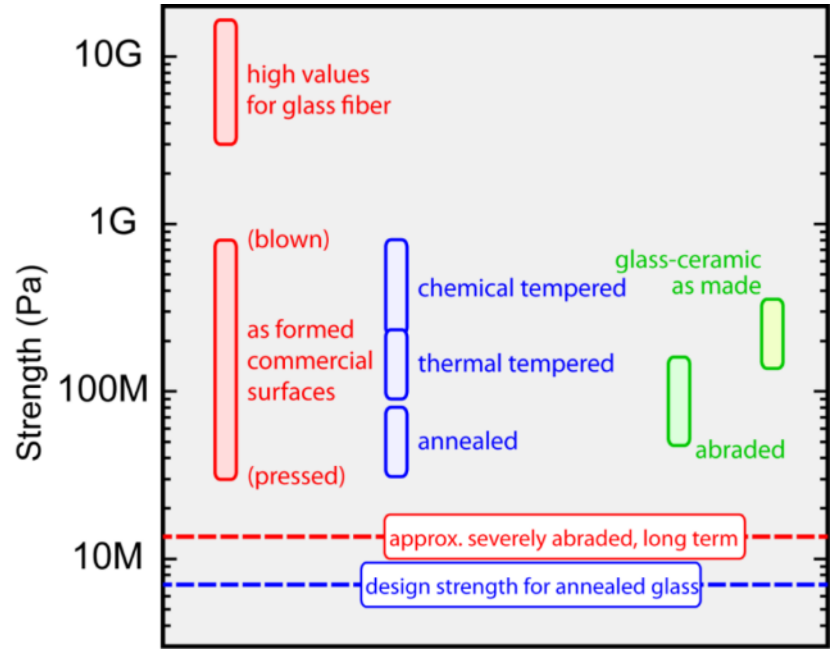


Glass Properties and Manufacturing

- Glass Composition
- Melting & Forming Process
- Secondary Processes
- Glass Handling

What influences the strength of glass?

- Theoretical strength of glass: ~14-30 GPa
- Typical (tensile) strength:
  - Bulk glass: ~10-150 MPa
  - Optical fiber: ~700 MPa -15 Gpa
- Practical strength of glass is an extrinsic property
  - Controlled by flaws
  - Determined by manufacturing and handling history (robots, rollers, finishing)
  - Statistical in nature



Glass Treatment Techniques

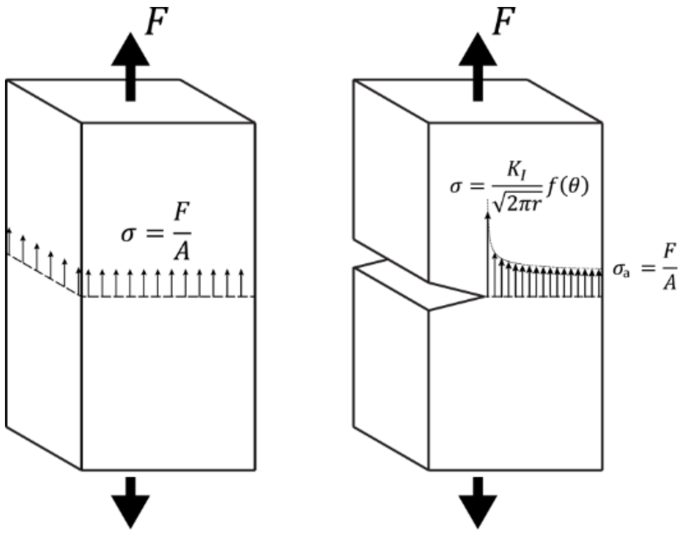
Stress intensity factor and fracture criterion

- Stress intensity factor (K_I):

$$K_I = Y\sigma_a\sqrt{a}$$

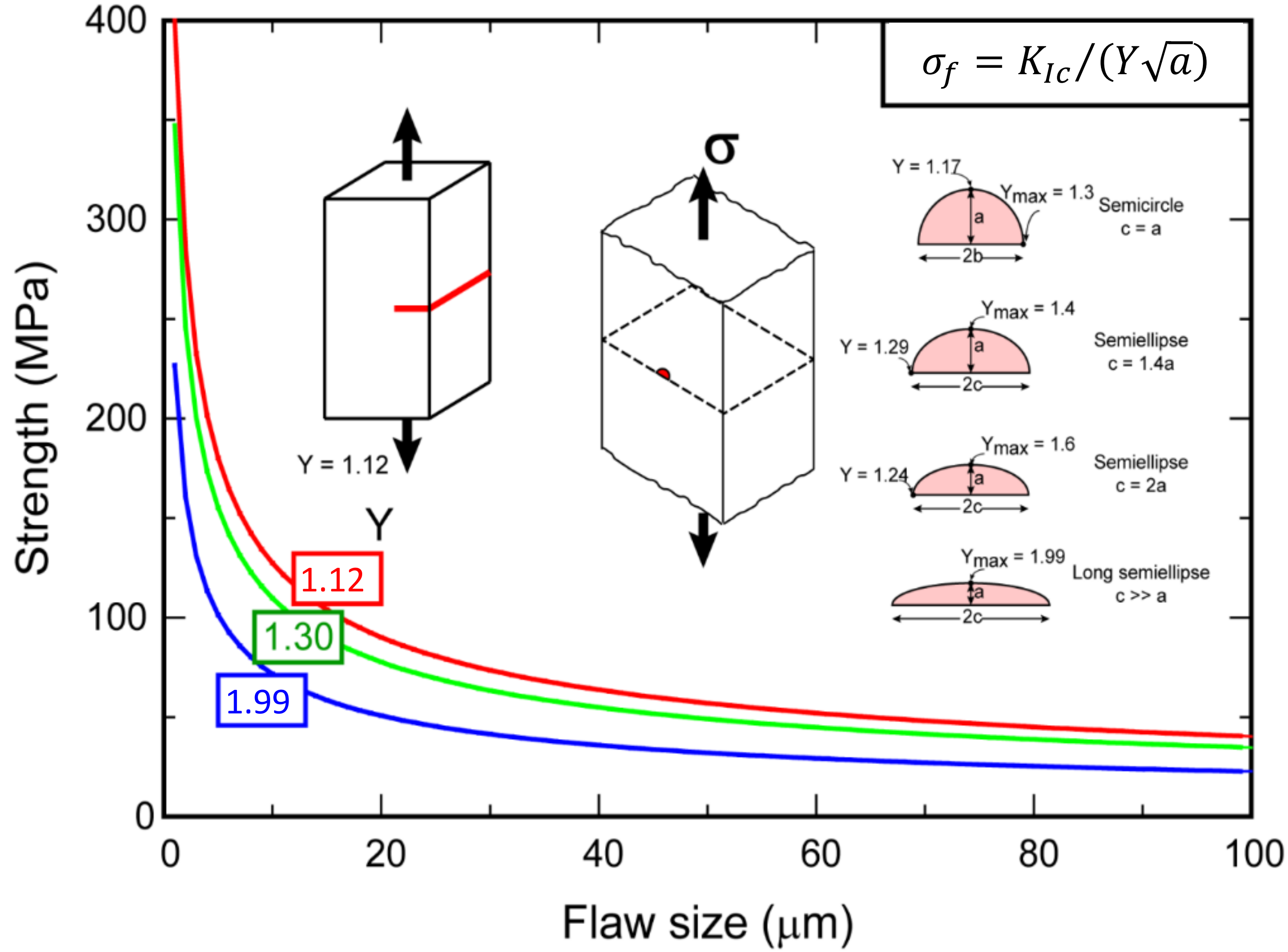
  - Y is the crack shape parameter
  - a is the flow depth
- What happens during loading to failure:
  - increase applied stress; → increase K_I
  - or increase flaw depth;
  - or both
- Failure occurs when $K_I \geq K_{Ic}$
- Fracture strength can be calculated as:

$$\sigma_f = \frac{K_{Ic}}{Y\sqrt{a}}$$



Reference: D. Broek, Elementary Engineering Fracture Mechanics, Springer, 1982.

Glass failure is dependent upon flaw type and depth in the presence of applied tensile stress field



How do we increase the strength of glass?

- Fracture strength of glass:

$$\sigma_f = \frac{K_{Ic}}{Y\sqrt{a}}$$

- Possible avenues for increasing fracture strength:
  - Increase fracture toughness
  - Reduce flaw depth (minimize damage introduction)
  - Reduce tensile stress experienced by flaws

Glass strength declines significantly with flaw size

Relationship between tensile stress and flaw size

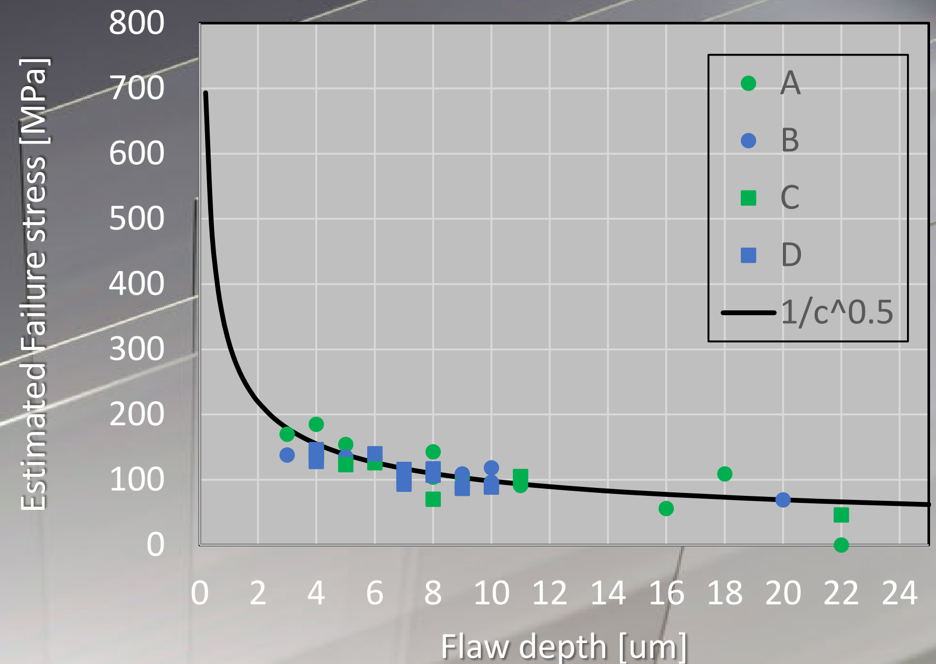
$$\sigma = \frac{1}{Y}\frac{K_{IC}}{\sqrt{\pi c}}$$

σ = Stress

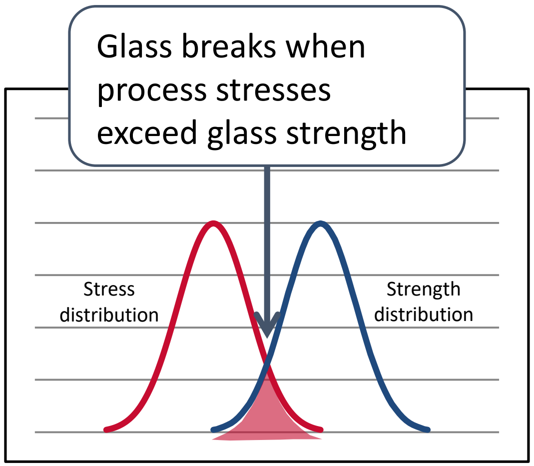
c = Crack Size

Y = Crack shape factor

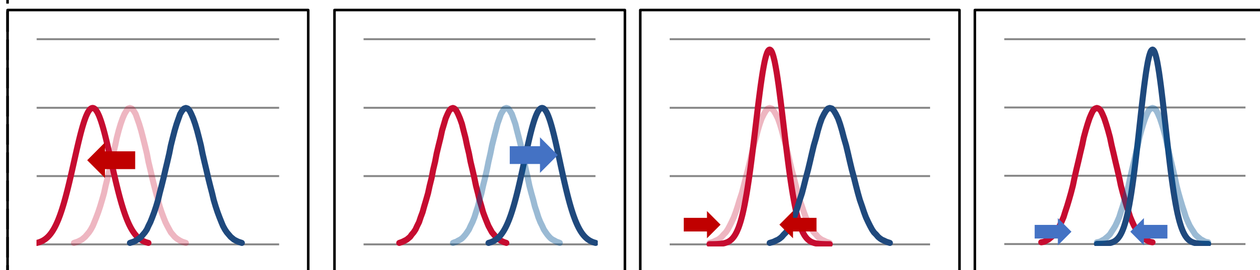
K_{IC} = Fracture Toughness



Material breakage can be avoided by reducing stresses in the process and strengthening the material used



Four ways to separate the distributions



Reduce mean stress by improving the conditions in which glass is used

Affected by the **user**

Increase mean strength by improving glass traits

Affected by the **glass manufacturer**

Narrow stress distribution by improving end-use consistency

Affected by the **user**

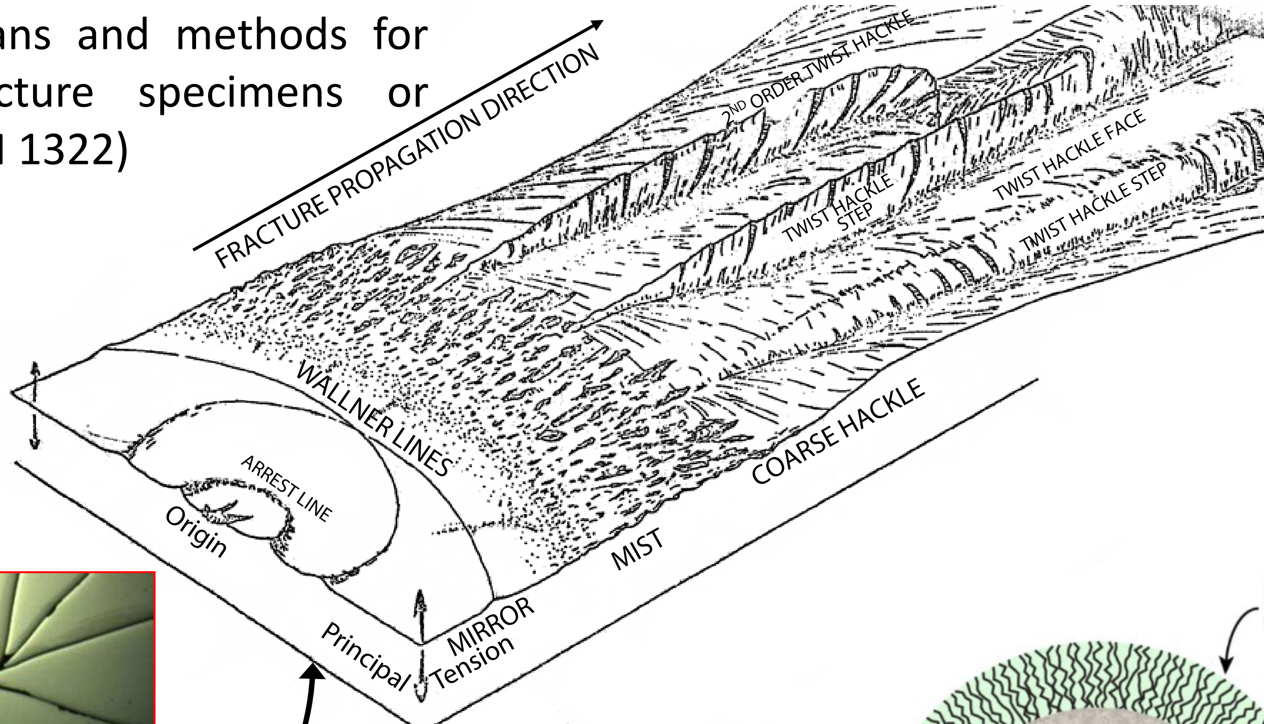
Narrow strength distribution by improving manufacturing consistency

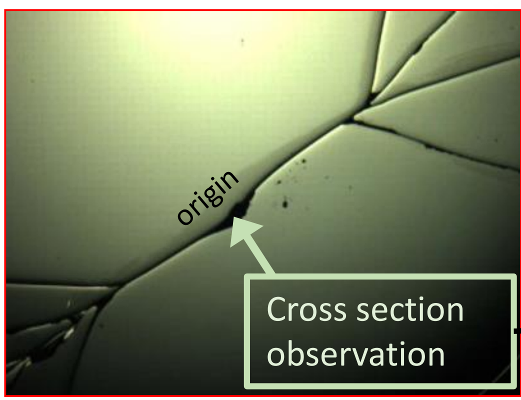
Affected by the **user and glass manufacturer**

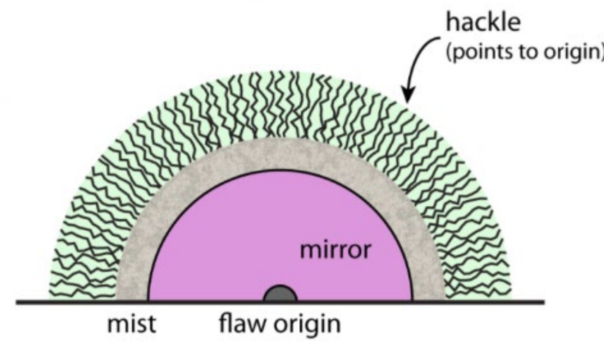
Glass survivability requires tight collaboration between glass manufacturer & user

Fracture markings can be used to determine the cause and stress condition leading to fracture

Fractography: Means and methods for characterizing fracture specimens or components (ASTM 1322)

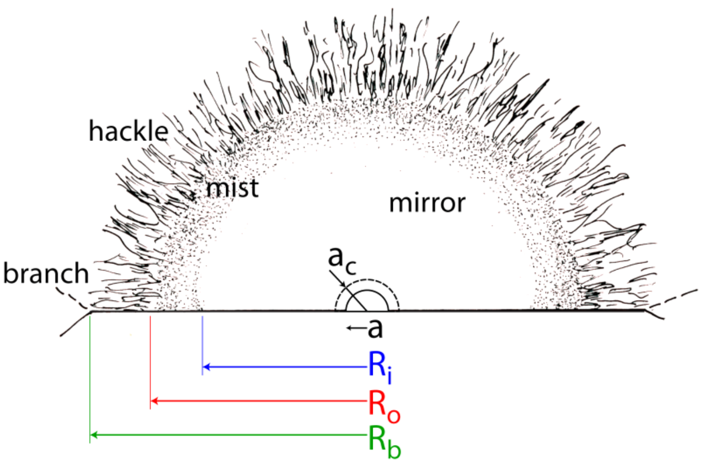




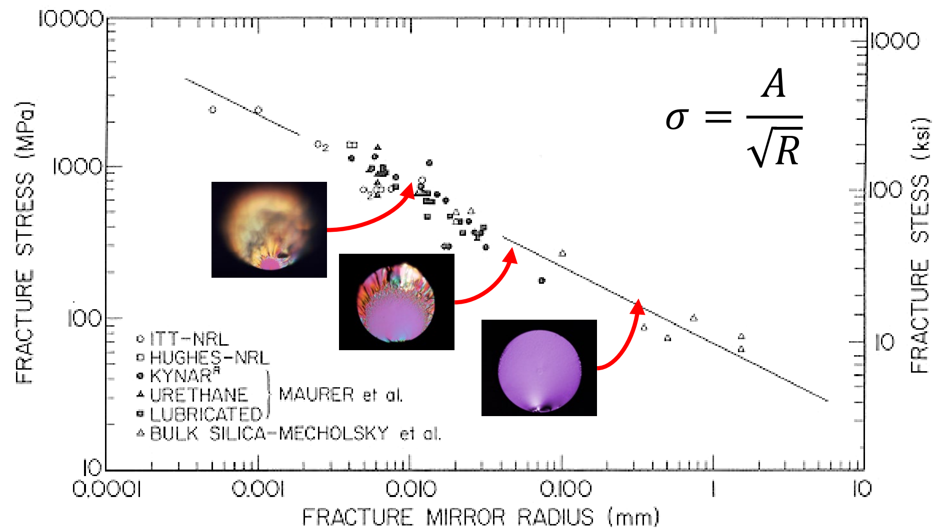


Fracture stress can be estimated from mirror size

- Mirror size has been related to failure stress
- Mirror historically measured at the intersecting points where the mist meets the material surface

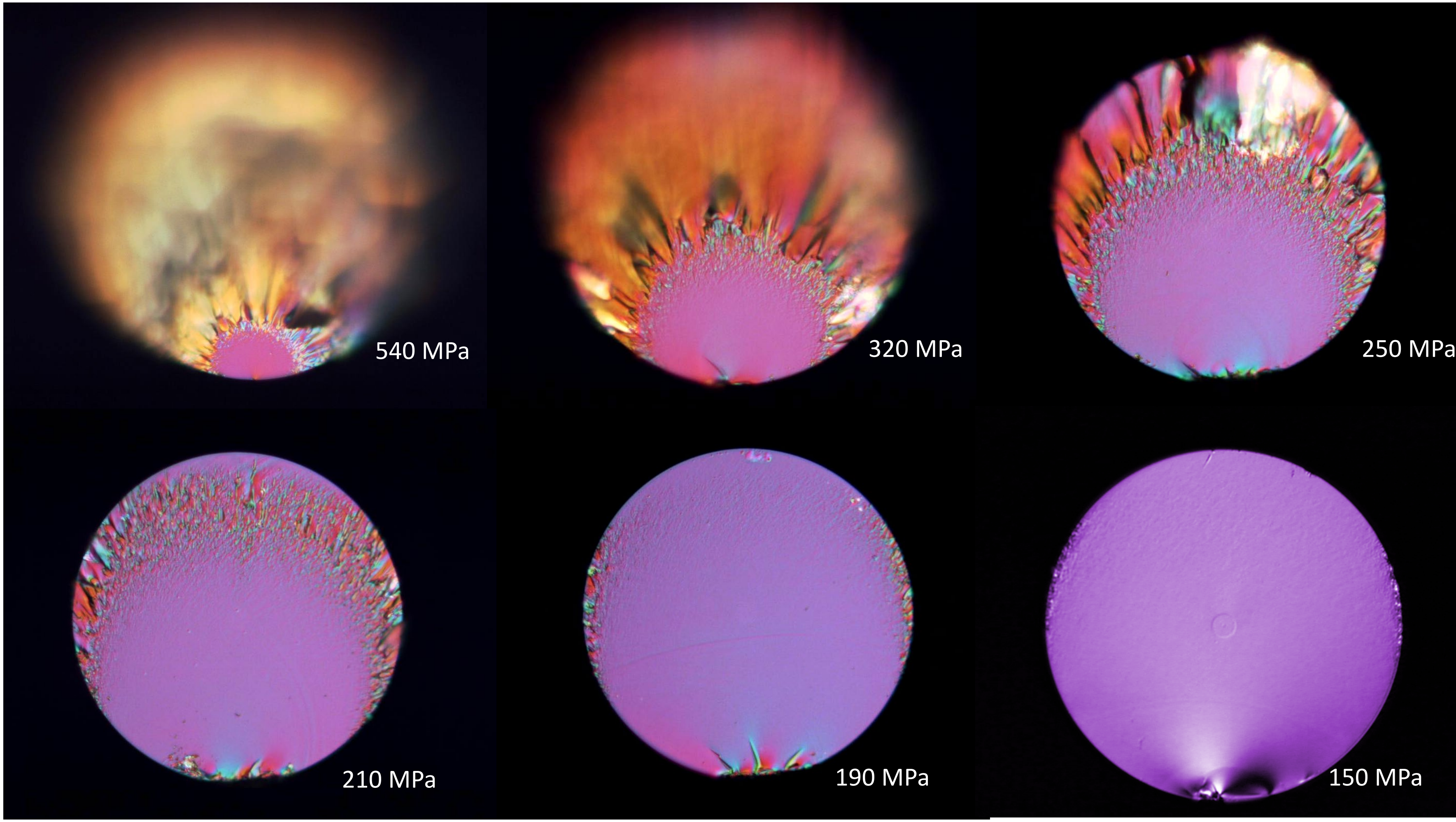


Reference: GD Quinn, "Fractography of Ceramics and Glasses" NIST Special Publication 960-16, 2007.



Reference: JJ Mecholsky, "Fracture Surface Analysis of Optical Fibers" Ceramics and Glasses of the Engineered Materials Handbook, Vol. 4, 1991

Size of fracture mirror correlates with fracture stress



Source: RJ Castilone, GS Glaesemann, TA Hanson, " Relationship between mirror dimensions and failure stress for optical fibers", Proceedings of SPIE Vol. 4639, 2002.

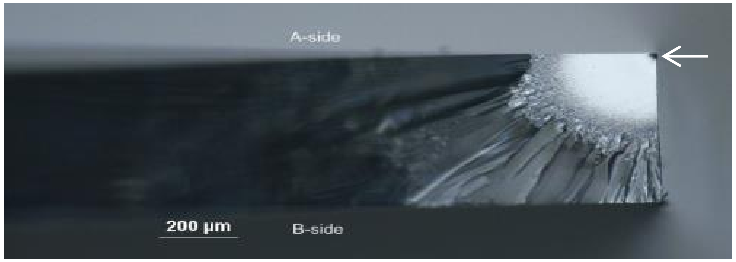
Example

Edge
Low stress

Damage at the cell cutting
(Panel maker)

Surface
Low stress

Damage at the assembling
(Assembling vendor)



Edge
High stress

Design issue of bezel
(Note PC maker)

What do we get from fractography?

- Fractography allows us to understand why and how a component failed (e.g. fiber, display panel, cover glass on mobile device)
- Knowing failure mode is the quickest path to solutions and new innovation
- Fractography also provides an insight to the relevant test methods during materials/product development

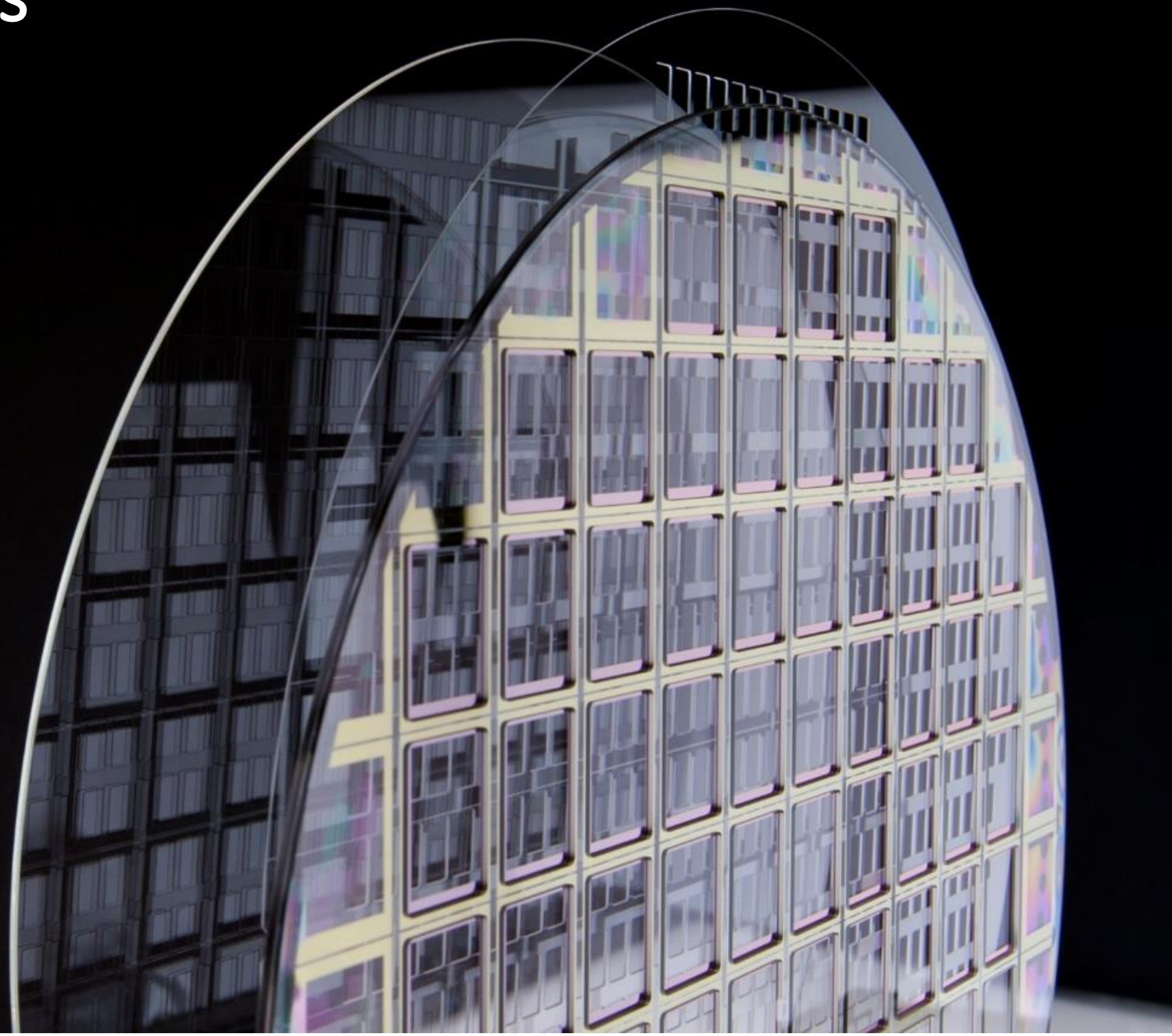
Quiz

1. What is the backbone of all glass?

2. Which 2D forming process creates a pristine, flat surface with no polishing required?

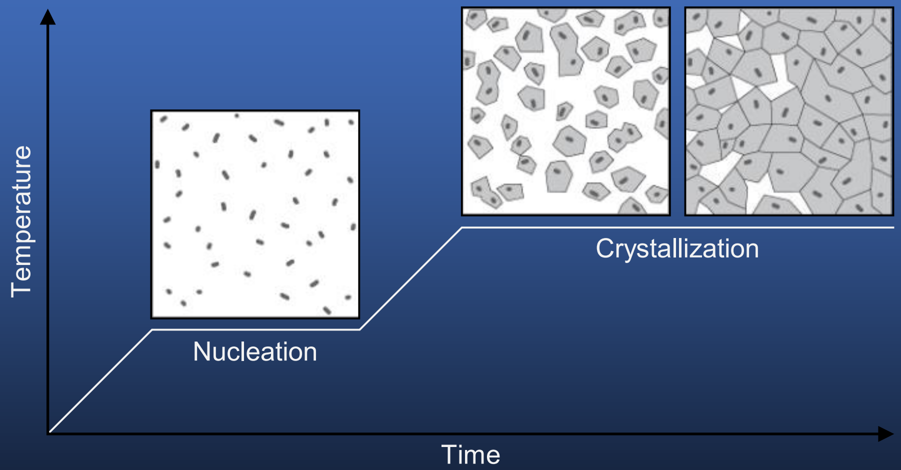
3. What controls the strength of glass?

3. Fundamentals of Glass-Ceramics And Applications



What makes a glass-ceramic?

The produced phase alters some measurable property of glass



Controlled crystallization can give new material properties → Resulting in glass-ceramics

Glass-ceramics were discovered accidentally by Don Stookey when he overheated a glass. It crystallized entirely, or cerammed.

Composition work led to Pyroceram®, ubiquitous (and mostly unbreakable) as Corningware®.

Dr. S. Donald Stookey receiving the National Medal of Technology from President Ronald Reagan, 1986.

The world of glass-ceramics includes diverse applications

Retainers for space shuttle tiles

Optical waveguide ferrules

Dental restorations and prostheses

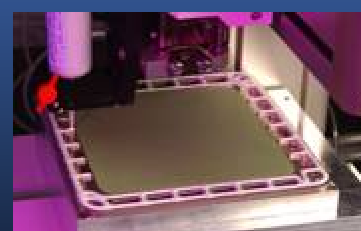
Ring laser gyros

CorningWare®

Stove cook top

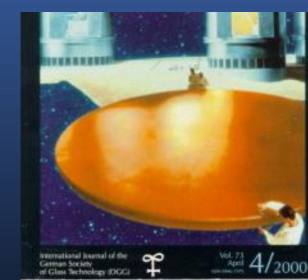
Woodstove windows

Architectural panels



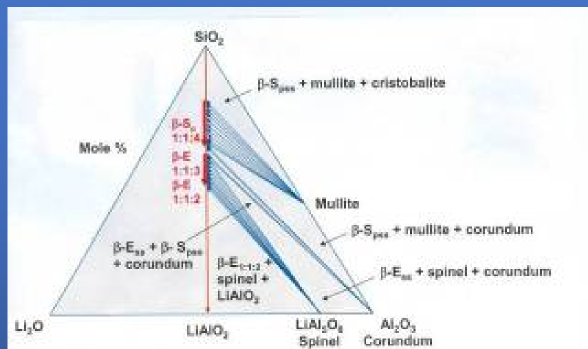
Seals for SOFCs

Radomes

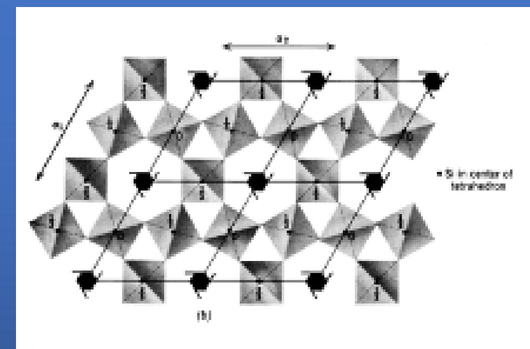


Telescope mirrors

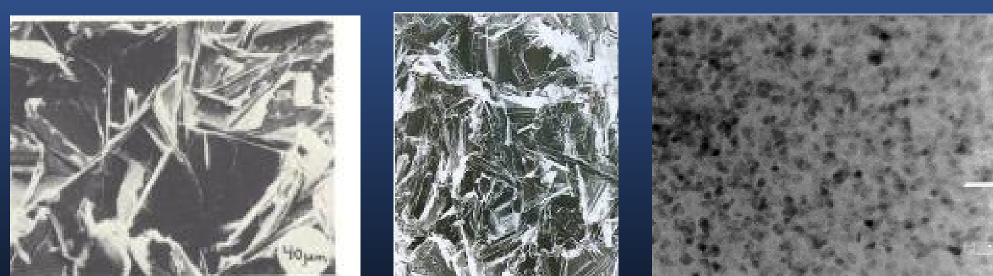
How do we design glass ceramics?



Stable glass composition



Mineral Phase Assemblage

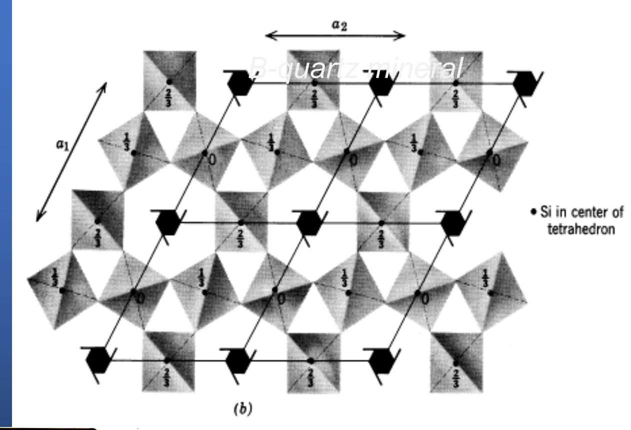


Crystalline microstructure

There are several types of glass-ceramics

Example: 3D silicates

- 3D networks of cross-linked tetrahedra
- Blocky, euhedral crystals
- Useful characteristics:
  - ✓ Low expansion
  - ✓ Transparency
  - ✓ Excellent chemical durability
- Applications:
  - ➢ Telescope mirrors,
  - ➢ Ring laser gyroscopes
  - ➢ Radiant cooktops
  - ➢ Cookware

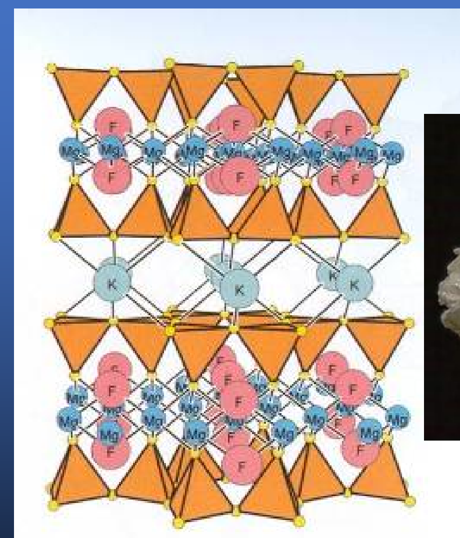


Electric cooktop

There are several types of glass-ceramics

Example: 2D silicates

- 2D layers of silica-alumina tetrahedra
- Crystals: Easily cleaved
- Useful characteristics:
  - ✓ Higher strength compared to 3D silicates
  - ✓ Better machinability than 3D silicates
- Applications:
  - ➢ Space shuttle components
  - ➢ High vacuum insulators & supports



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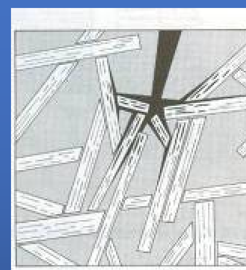
There are several types of glass-ceramics

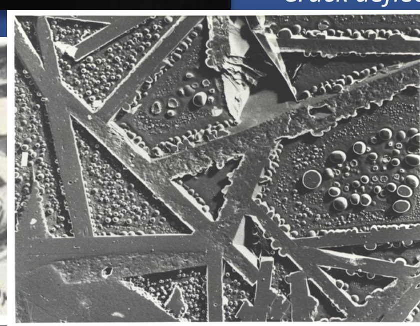
Example: Machinable glass-ceramics



Fracture propogation

Crack deflection & blunting

Fractured surface



Polished/etched surface

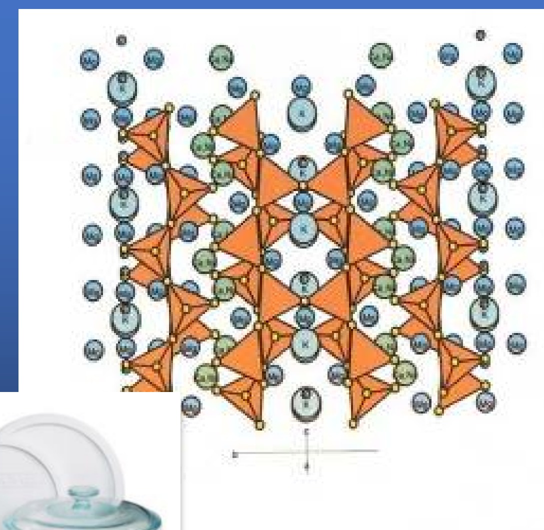
Density g/cm^3	2.52
CTE 25°-300°C ppm	9.3
Young's modulus GPa	67
Poisson's ratio	0.29
Knoop hardness	250
Flexural strength (MOR) MPa Compressive strength	94 345
Fracture toughness MPa·m$^{1/2}$	1.53
Dielectric constant 25°C 1 KHz 8.5 GHz DC volume resistivity ohm-cm	6.03 5.67 $>10^{16}$
Thermal conductivity W/m°C	1.46

There are several types of glass-ceramics

Example: Chain silicates

- One-dimensional: Single or multiple chains of tetrahedra
- Crystals: rods, blades, laths, asbestiform
- Useful characteristics:
  - ✓ Highest strength, toughness
  - ✓ Delayed breakage resistance
- Applications
  - ➢ Tableware
  - ➢ Architectural products
  - ➢ Industrial products
  - ➢ Bone implants

Nephrite jade boulder, British Columbia

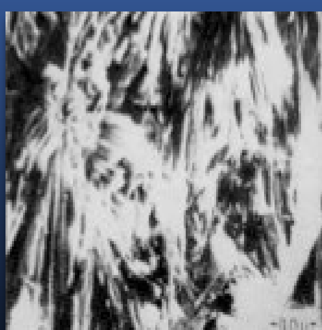


There are several types of glass-ceramics

Example: Chain silicates

Natural jadeite (Bradt et al., 1973)

Enstatite GC



Nephrite jade (Bradt et al., 1973)

Canasite GC

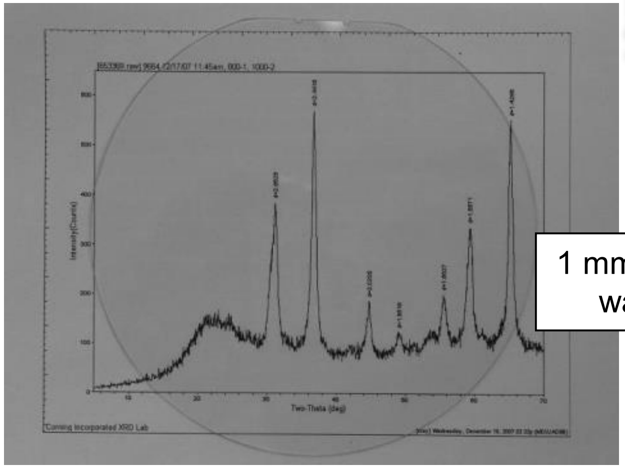
Radial interlocking growth

Step fractures: Toughening mechanism

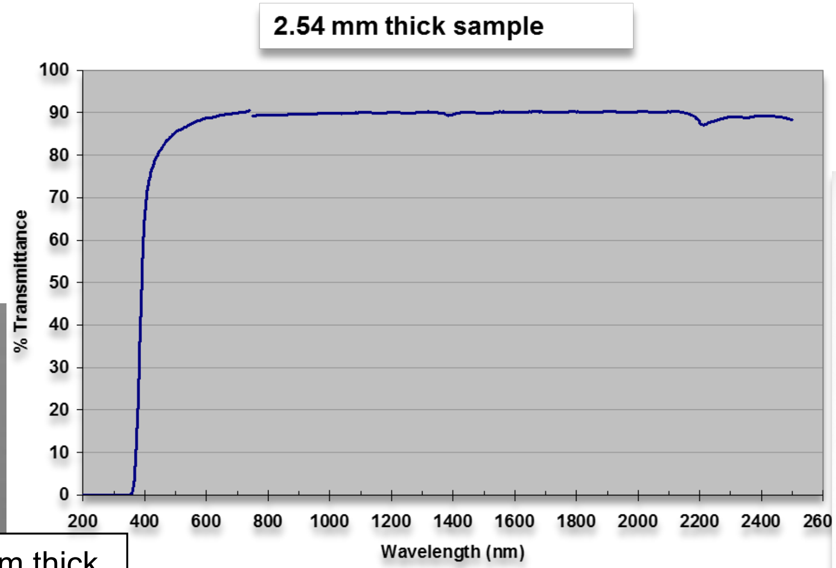
	Flexural strength (abraded) MPa	Young's modulus GPa	Fracture toughness MPa·m$^{1/2}$
Natural jade			
Jadeite	100	200	7.1
Nephrite	210	130	7.7
Glass-ceramics			
Canasite	300	82	5.0
F-K-richterite	220	87	2.0
Enstatite	200	140	4.0
Cerabone® A-W	215	118	2.0
Soda-lime glass	*~50*	*73*	*0.75*

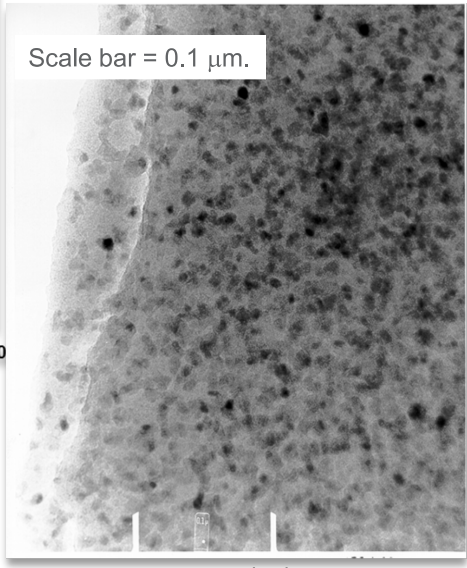
There are several types of glass-ceramics

Example: Transparent spinel glass-ceramic



1 mm thick wafer

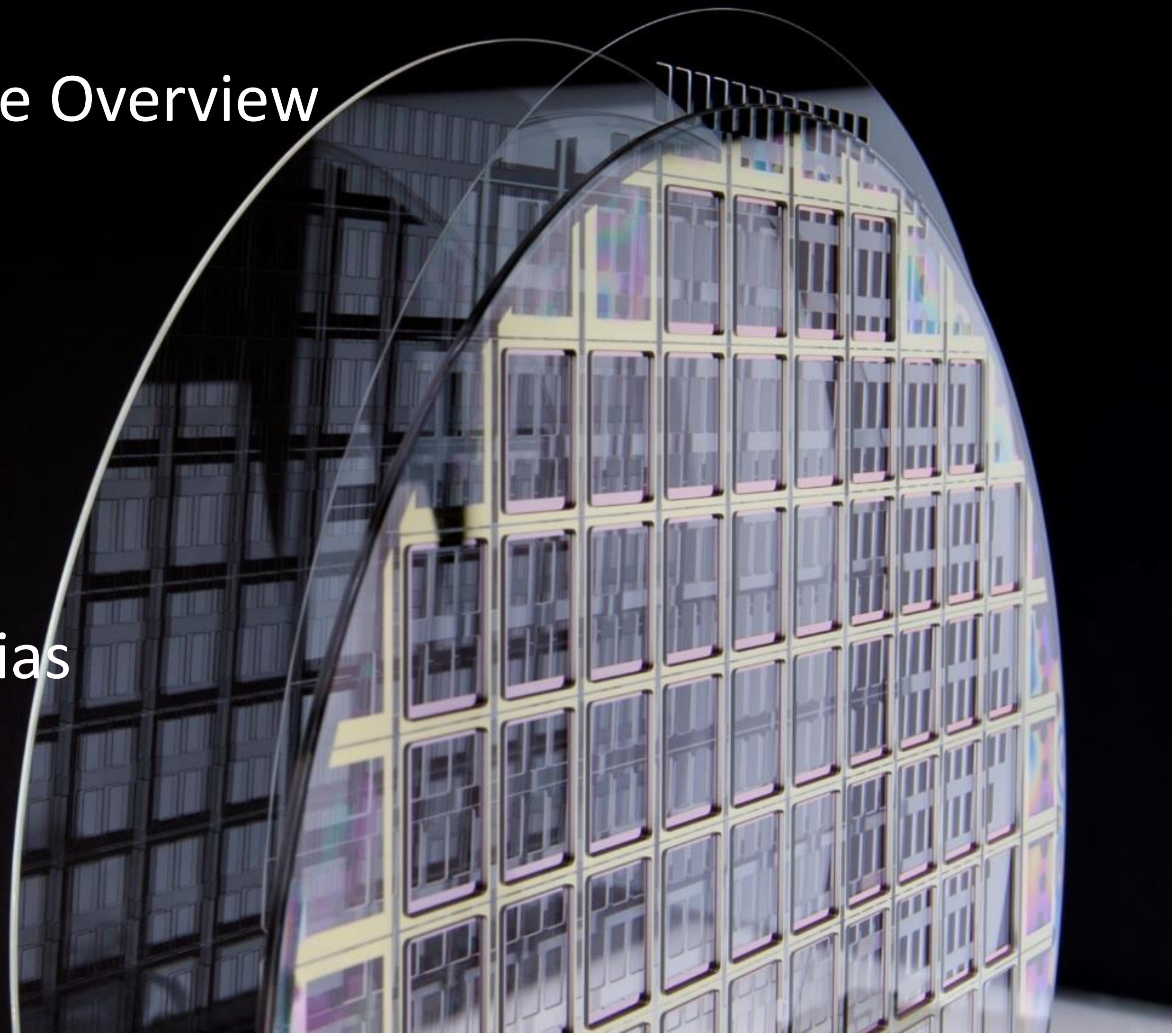




TEM micrograph showing nanoparticles

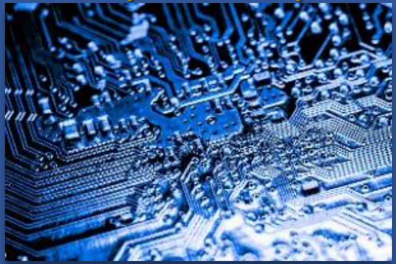
4. Select Applications and Markets

- Consumer Device Overview
- Glass Carriers
  - For Si Thinning
  - For Fan-Out
- Through Glass Vias



Four trends are driving increased glass adoption in consumer devices

1. Faster, more compact chips



Advanced packaging

2. Faster, seamless connections

RF antennas & filters

3. Highly accurate, miniaturized

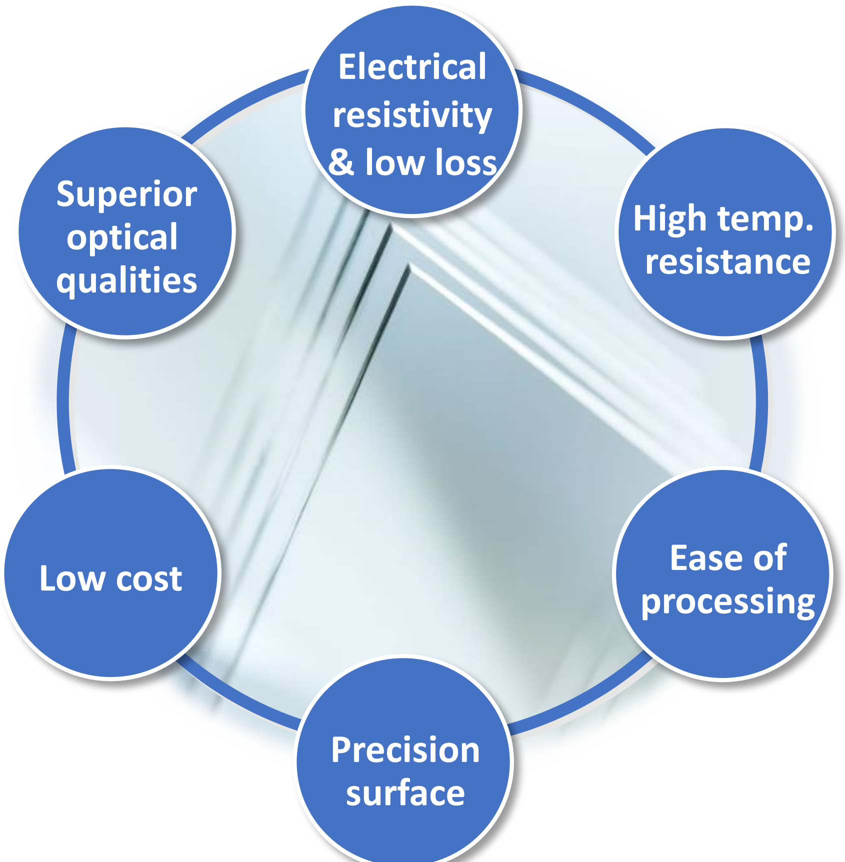
Wafer-level optics

4. Engaging, immersive

Waveguide displays for augmented reality

Glass-based solutions are improving all of these applications

Why is glass an advantaged material for these applications?



Examples:

Superior optical qualities – DOE

Low RF loss – RF antennas and filters

High temp. resistance - Advanced packaging

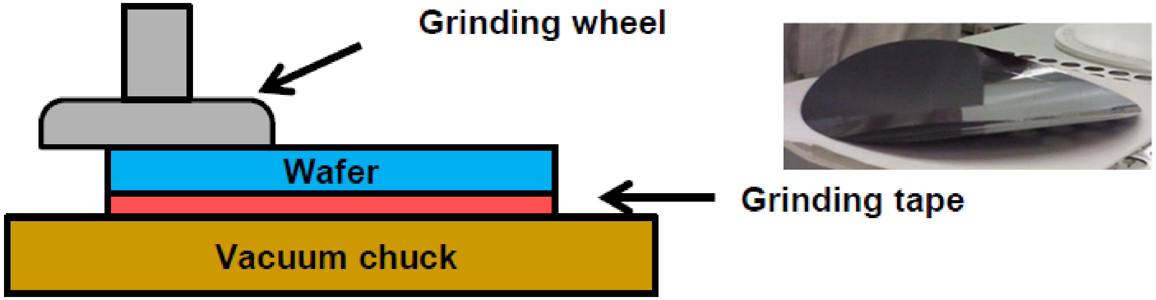
Precision surfaces – Waveguide displays

The inherent properties of glass make it an excellent material of choice for applications in electronics

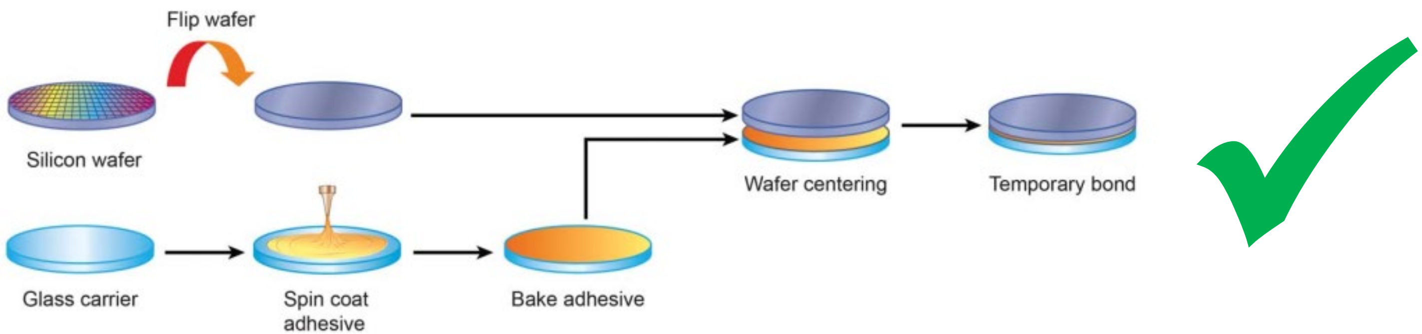
		Applications	
		Carriers for Fan-Out Packaging	RF Components
Properties of glass	Range of CTEs in fine granularity	✓	✓
	Optical transparency	✓	
	Low electrical loss	✓	✓
	Flatness & smoothness	✓	✓
	Stiffness	✓	✓
	Variety of thicknesses	✓	✓
	Scalability	✓	✓

Glass Carriers for Si Thinning

Ultra-thinning of Si requires a rigid carrier



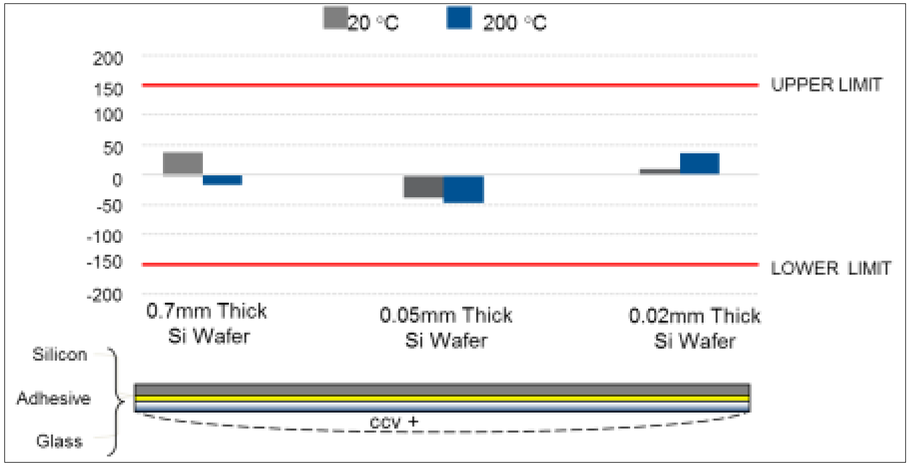
When wafers are thinned to <<100um or require post-thinning processing, glass carrier is a preferred choice



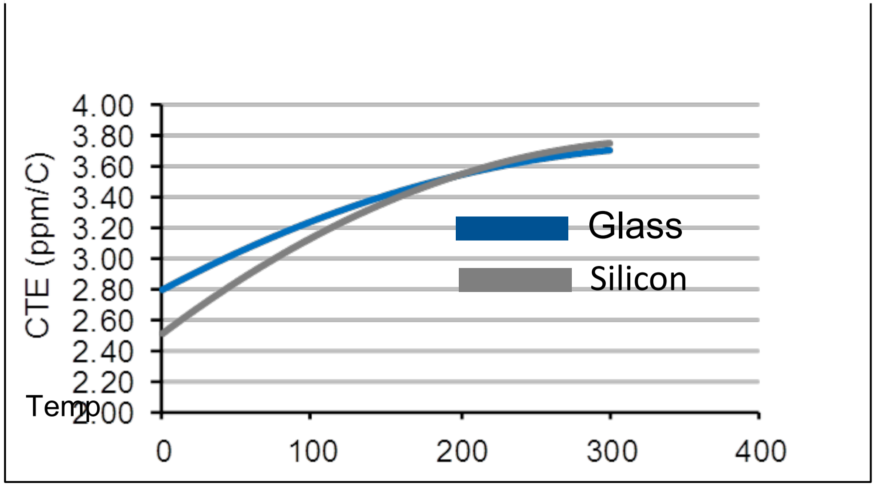
Wafer bow during thinning and post processing is a function of relative CTE Of glass, Si, and adhesive

Coefficient Thermal Expansion (CTE) matched to silicon

Wafer Stack Bow vs. Si Thickness & Temperature

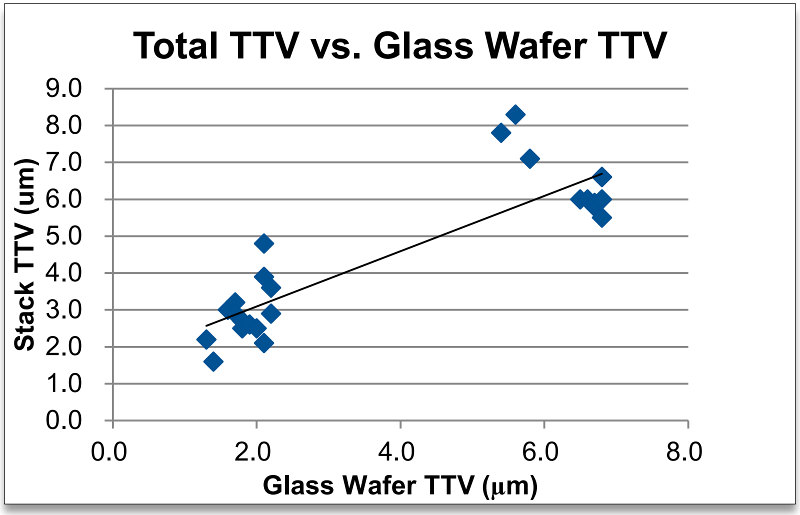


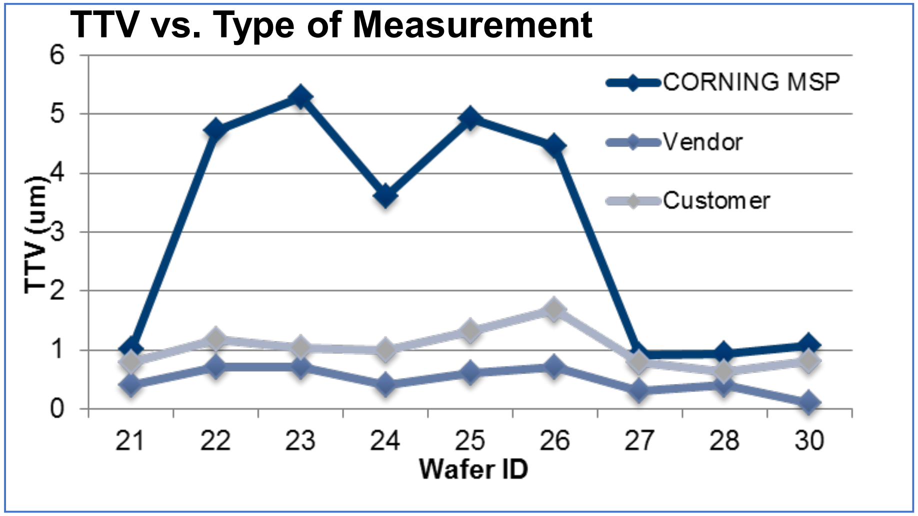
Instantaneous CTE vs. Temperature



- A target maximum BOW of 150µm during processing is achievable due to good expansion matching between the glass carrier and Si wafer.
- For many next generation I/C designs, wafer thinning leads to an **increase** in total stack-up CTE, requiring a higher CTE carrier to match.

Total Thickness Variation (TTV)



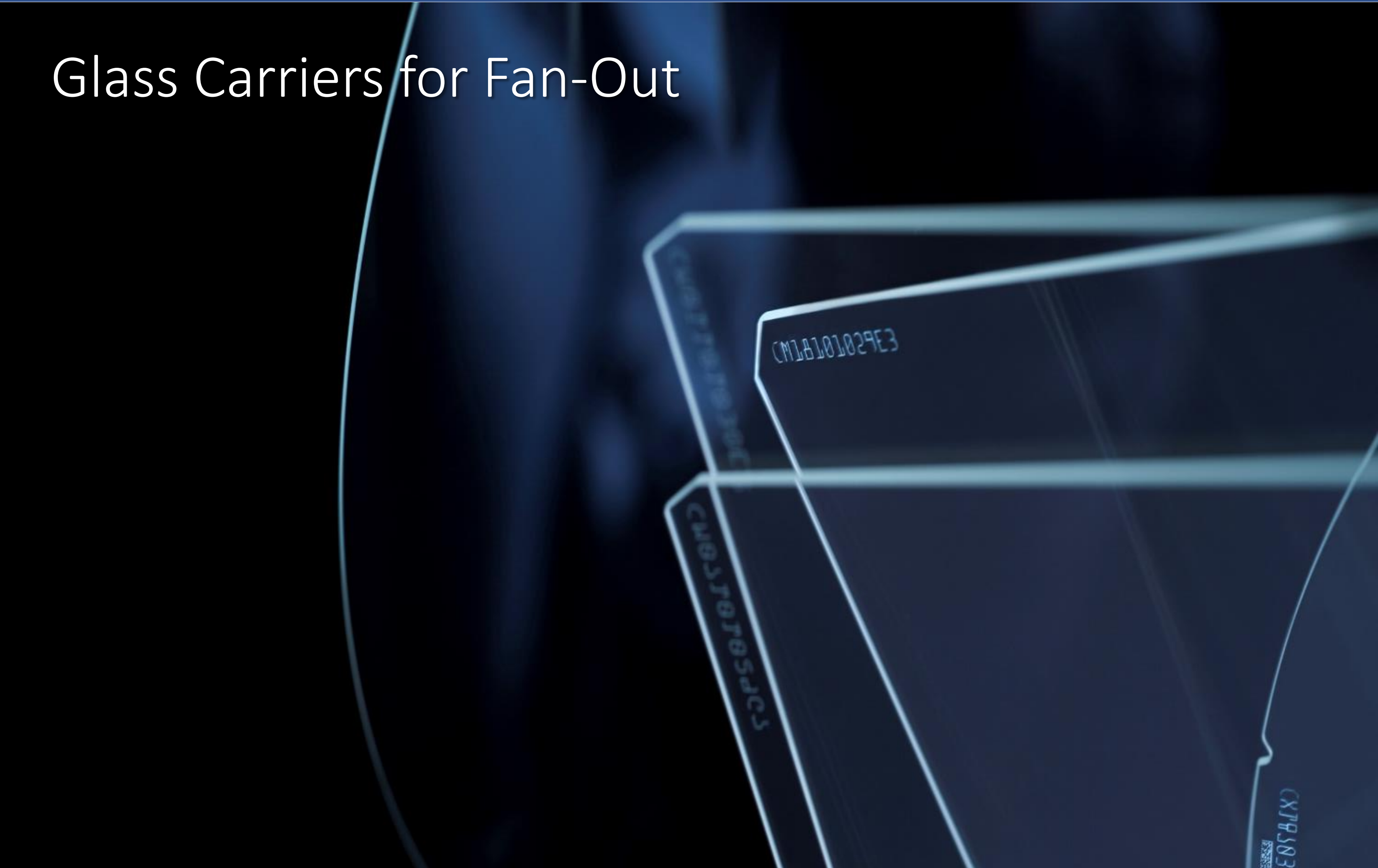


- Corning wafers (SG 3.4) of specified TTV ("low" and "high") used with 3M WSS to study effect of wafer TTV on bonded stack TTV
  - Data is highly correlated (i.e. low glass TTV gives low wafer stack TTV)

- Glass wafers from another established wafer supplier reporting TTV < 1 μm as based on only 5 measurements/wafer
  - Actual thickness variation as measured by MSP, was much greater than 1 μm, which can clearly impact bonded stack TTV

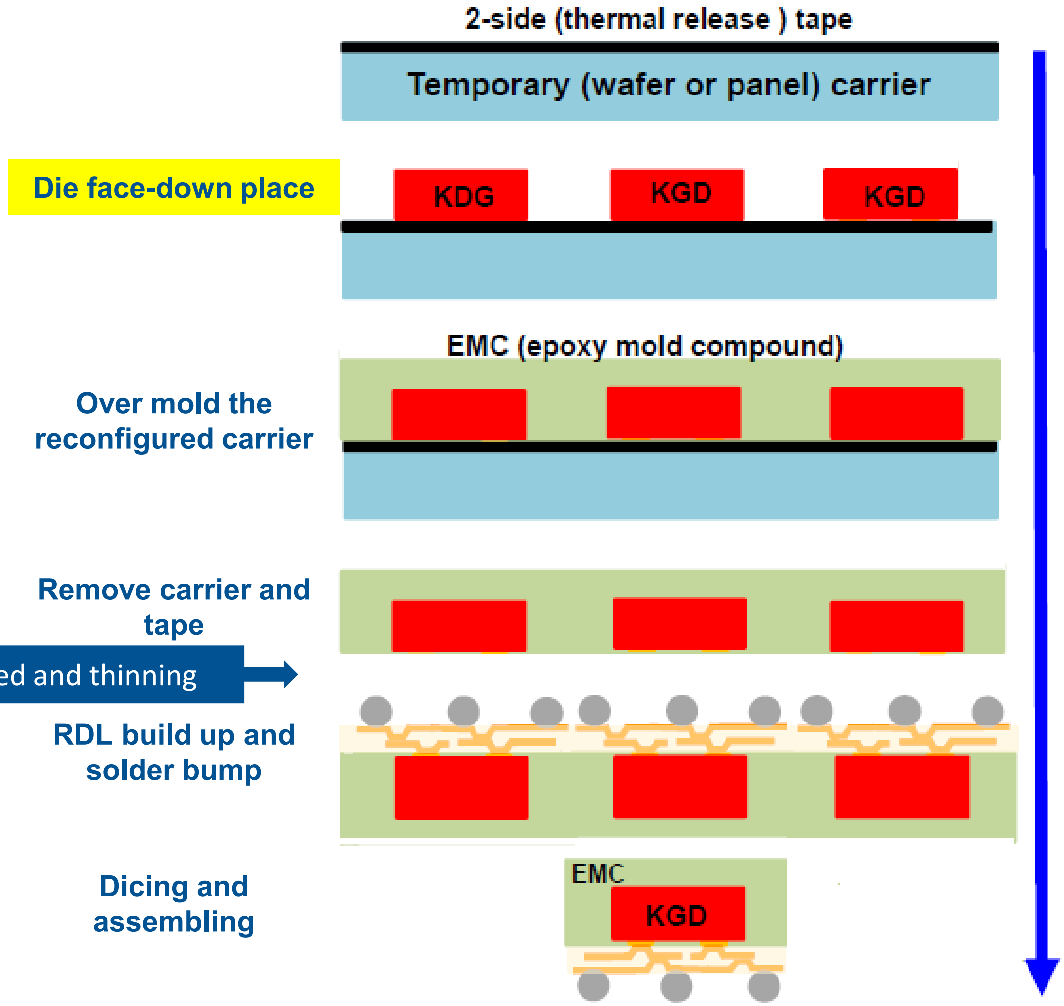
Data taken using 3M WSS process

Glass Carriers for Fan-Out



Process flow:
Chip first fan-out wafer-level packaging

- This technology had been developed for a long time. First patent was filed by Infineon in 2001.
- The process had been improved for larger size and thinner package.
- Glass is an attractive carrier material



Understanding in-process warp

CTE mismatch in carrier applications induces in-process warp

Assuming bi-axial bending, the bending curvature due to CTE mismatch and high process temperature is:

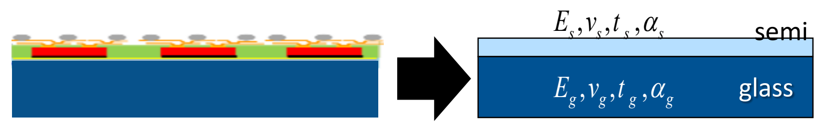
$$\kappa = \frac{6\left(\alpha_s - \alpha_g\right)\left(T_{\text{process}} - T_{\text{room}}\right)(t_g + t_s)t_g t_s}{\left[\frac{E_g\left(1-v_s\right)}{E_s\left(1-v_g\right)}t_g^4 + \frac{E_s\left(1-v_g\right)}{E_g\left(1-v_s\right)}t_s^4 + 2t_g t_s\left(2t_g^2 + 3t_g t_s + 2t_s^2\right)\right]}$$

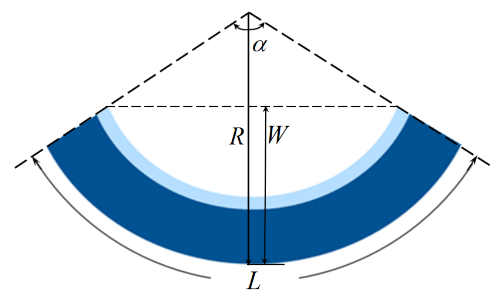
and the warp is:

$$W = R\left(1-\cos\left(\frac{\alpha}{2}\right)\right) = \frac{1}{\kappa}\left(1-\cos\left(\frac{\kappa L}{2}\right)\right)$$

$$\approx \frac{3L^2\left(\alpha_s - \alpha_g\right)\left(T_{\text{process}} - T_{\text{room}}\right)(t_g + t_s)t_g t_s}{4\left[\frac{E_g\left(1-v_s\right)}{E_s\left(1-v_g\right)}t_g^4 + \frac{E_s\left(1-v_g\right)}{E_g\left(1-v_s\right)}t_s^4 + 2t_g t_s\left(2t_g^2 + 3t_g t_s + 2t_s^2\right)\right]}$$

$$\approx 0.75L^2 \Delta\alpha \ \Delta T \ \frac{E_s\left(1-v_g\right)}{E_g\left(1-v_s\right)} \frac{t_s}{t_g^2}$$



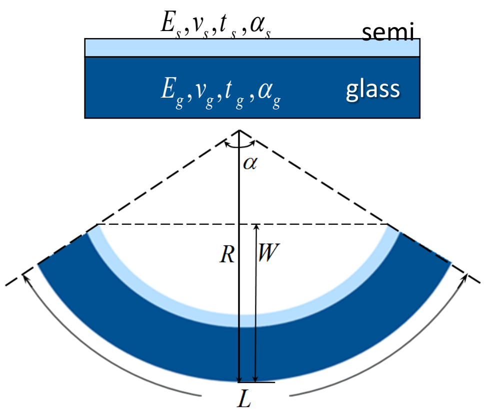


$$R = 1/\kappa \qquad \alpha = L/R = \kappa L$$

E : Young's modulus; v : Poisson's ratio; t: Glass thickness;
α : Coefficient of thermal expansion; T : Temperature.
g: glass; s: semiconductor layers (MC + redistribution layers + die)

Understanding in-process warp

CTE mismatch in carrier applications induces in-process warp



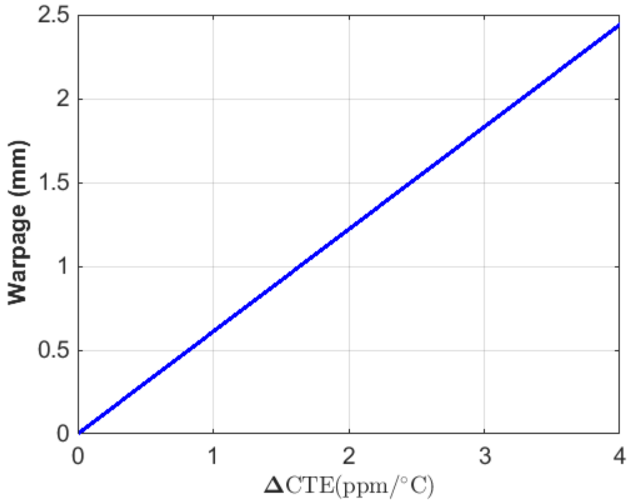
$$\approx 0.75 L^2 \Delta\alpha\ \Delta T\ \frac{E_s\left(1-v_g\right)}{E_g\left(1-v_s\right)} \frac{t_s}{t_g^2}$$

Under typical fan-out conditions, in-process warp follows a simplified formula showing its dependence on:

1. CTE mismatch between glass and the composite semi material
2. Glass Young's modulus
3. Square of glass thickness

Levers to control in-process warp

Decreasing ΔCTE between carrier and semi



$L = 300\text{mm}$

$E_g = 70\text{GPa};\ E_s = 20\text{GPa};$

$v_g = 0.22;\ v_s = 0.35;$

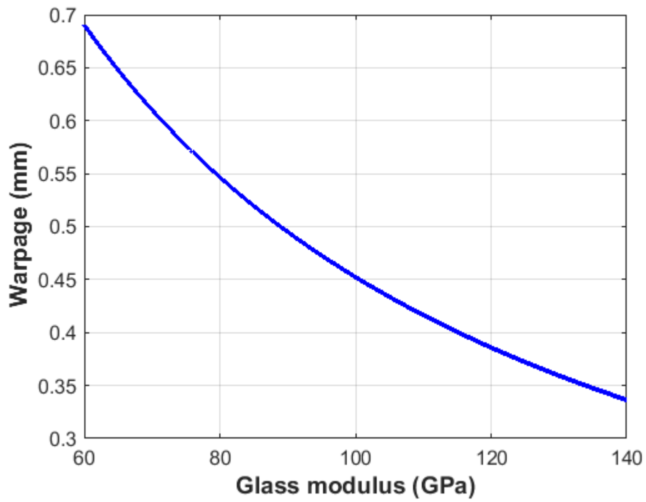
$t_g = 1.1\text{mm};\ t_s = 0.15\text{mm};$

$T_{room} = 20^\circ\text{C};\ T_{process} = 250^\circ\text{C};$

Perfect CTE match is desirable, but not possible due to composite semi CTE changing in process

Levers to control in-process warp

Increasing the modulus of the carrier



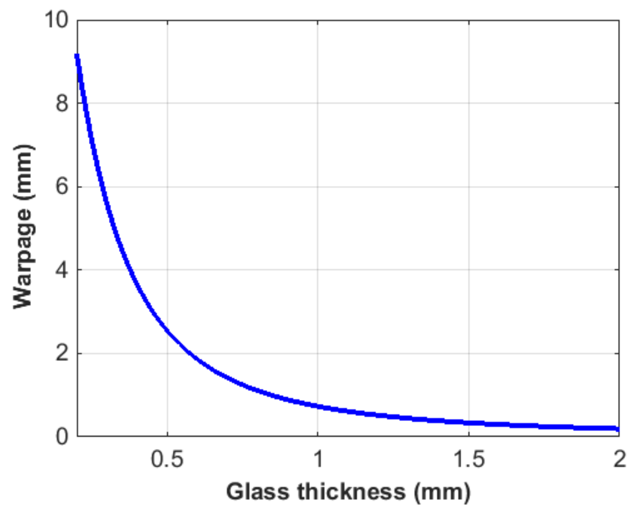
$L = 300\text{mm}$

$$E_s = 20\text{GPa};$$
$$v_g = 0.22;\ v_s = 0.35;$$
$$t_g = 1.1\text{mm};\ t_s = 0.15\text{mm};$$
$$\Delta\text{CTE} = 1.0\text{ppm}/^{\circ}\text{C};$$
$$T_{\text{room}} = 20^{\circ}\text{C};\ T_{\text{process}} = 250^{\circ}\text{C};$$

Warp is inversely proportional to the Young's modulus of the carrier

Levers to control in-process warp

Increasing the thickness of the carrier



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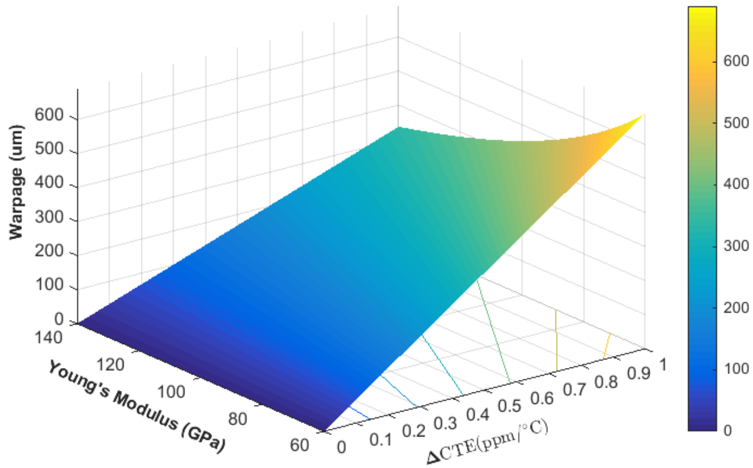
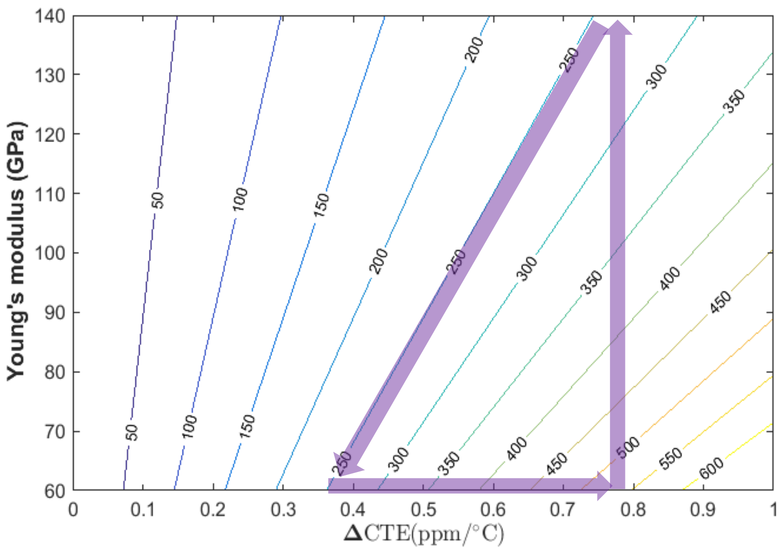
$$\Delta\text{CTE} = 1.0\text{ppm}/^{\circ}\text{C};$$
$$T_{\text{room}} = 20^{\circ}\text{C};\ T_{\text{process}} = 250^{\circ}\text{C};$$

Warp is inversely proportional to carrier thickness squared, but returns diminish beyond 1mm

Levers to control in-process warp

ΔCTE is part of fan-out reality





$E_s = 20\text{GPa};$

$v_g = 0.22;\ v_s = 0.35;$

$t_g = 1.1\text{mm};\ t_s = 0.15\text{mm};$

$T_{room} = 20^\circ\text{C};\ T_{process} = 250^\circ\text{C};$

L=300mm.

Higher Young's modulus helps overcome the ΔCTE mismatch challenge. Purple triangle maps out effect of YM going from 60GPa to 140GPa for warp of 250um: ΔCTE tolerance more than doubles.

These components are important for glass carriers

Component	Role	Expansion	Density	Modulus	Hardness	Durability	Transmission
SiO_2	NF	-	-	-	-	+	
Al_2O_3	NF	-	+	+	+	+	
B_2O_3	NF	-	-	-	-	+	
Li_2O	M	+		-	-	-	
Na_2O	M	+		-	-	-	
K_2O	M	+	+	-	-	-	
MgO	M			+	+	+	
CaO	M			+	+	+	
TiO_2	C		+	+	+	+	-
ZrO_2	NF/M		+	+	+	+	
Sb_2O_3	F	+	+	-	-	+	
SnO_2	F			+	+	+	

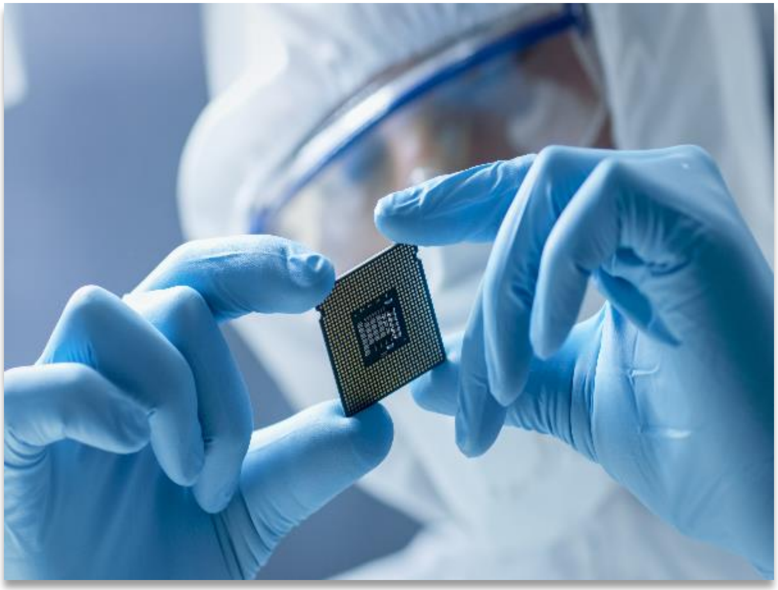
Key
+ = Component increases this property
- = Component decreases this property
 = Component has little effect on this property

NF: Network Former
M: Modifier
C: Colorant
F: Finer

Glass scientists tailor chemical compositions to customers requirements

Real-world customer challenges

Additional considerations



Product

- CTE mismatch is unavoidable due to different materials added during fan-out
- Very high YM may introduce failure modes not yet well understood due to high stress
- Too high a carrier thickness limits the Z-height of the package

Material availability and consistency

- Long lead times for carrier samples result in delayed package development
- Changes in carrier material during MP ramp may create issues

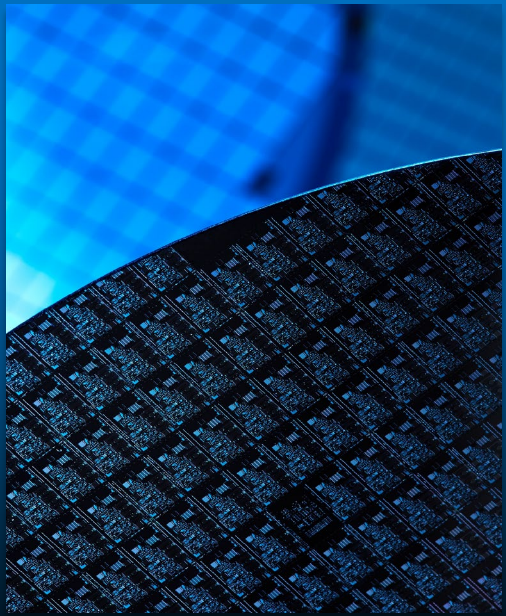
CORNING
Precision Glass Solutions

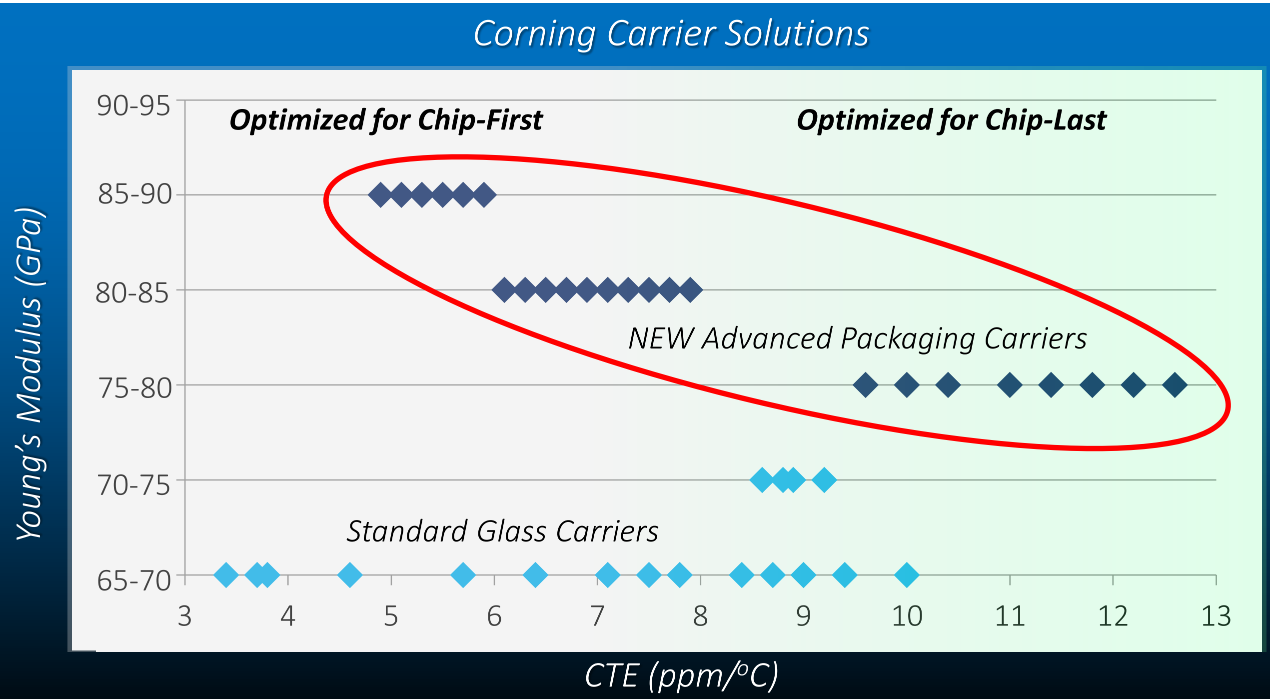
Introducing Advanced Packaging Carriers

Up to 40% reduction in customers' in-process warp

- ✓ Fine granularity of CTEs
- ✓ High stiffness
- ✓ 4-6 week sample lead time

Corning has tailored its glass carriers by Young's modulus and CTE to meet customers' requirements for advanced packaging

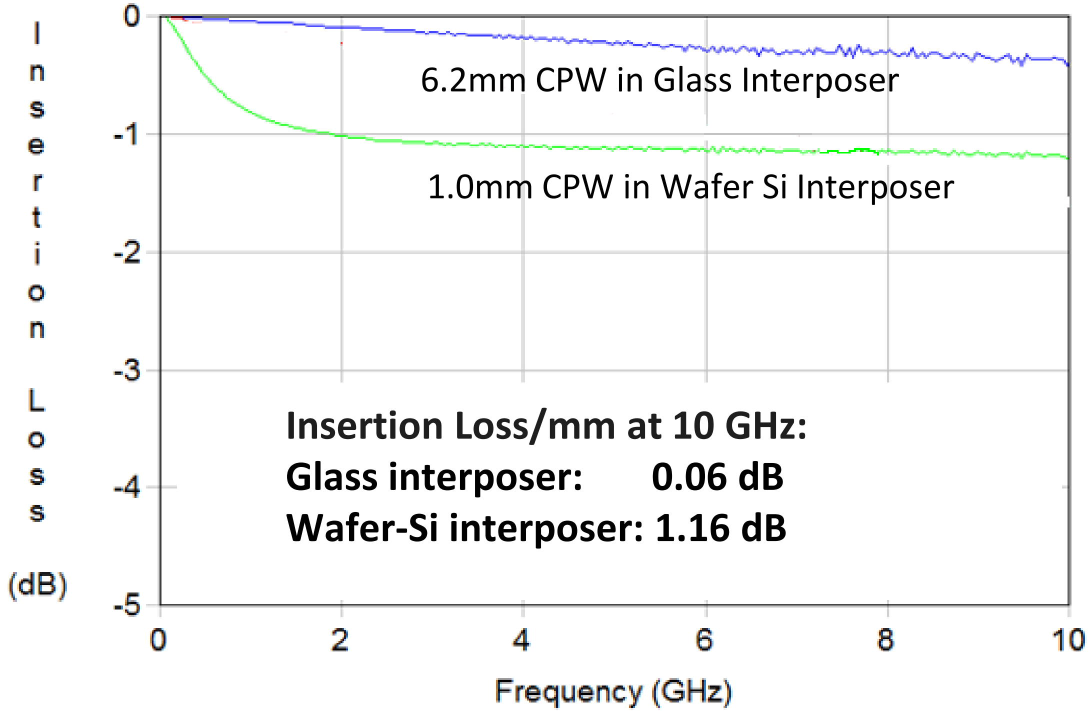




Through Glass Vias (TGVs)

Glass electrical properties significantly reduce signal loss

Signal Loss Measured at Georgia Tech

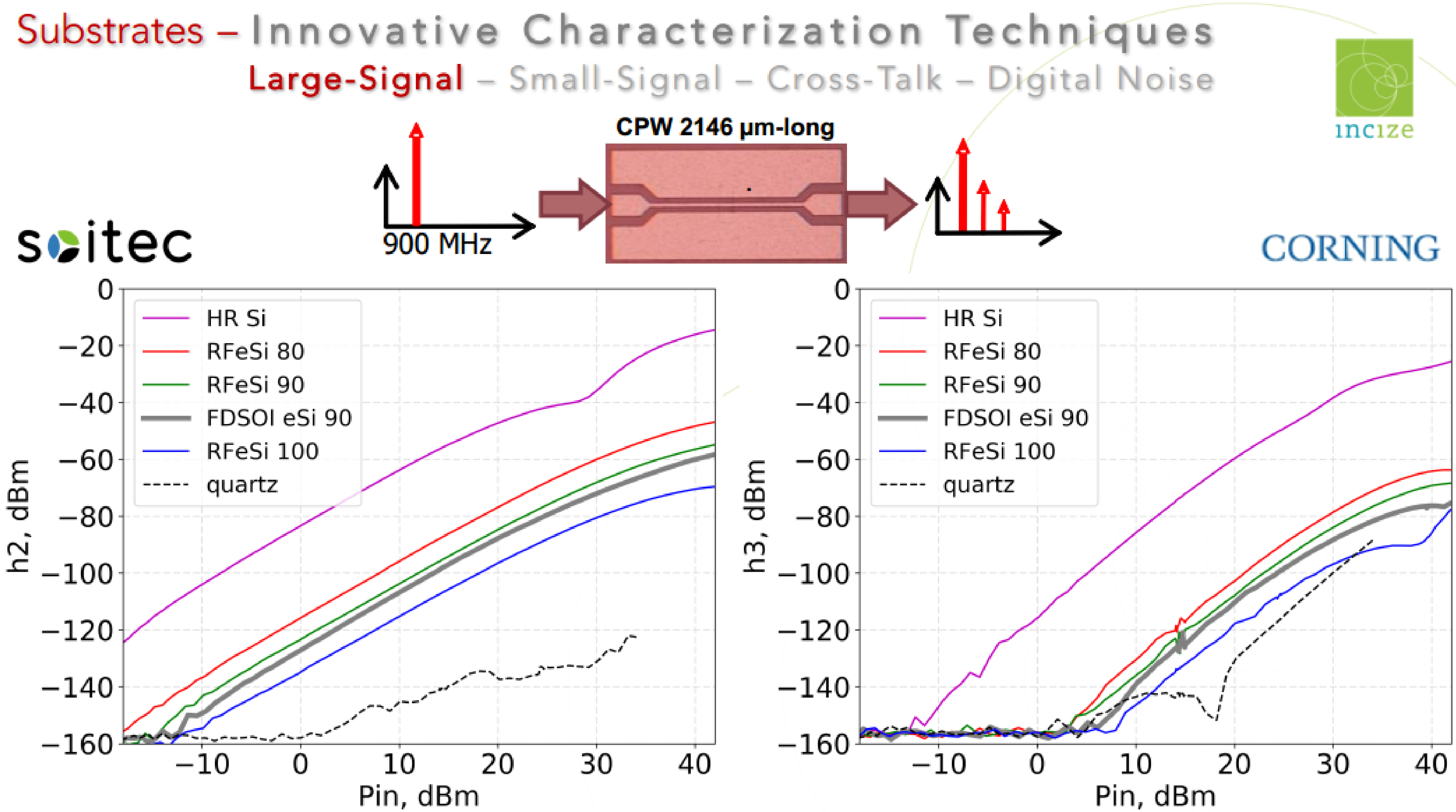


CPW = Coplanar Waveguide

10x lower signal loss in glass for a 6x longer interconnect than silicon (~60x lower leakage improves power efficiency)

Source: GaTech PRC

Glass shows superior linearity

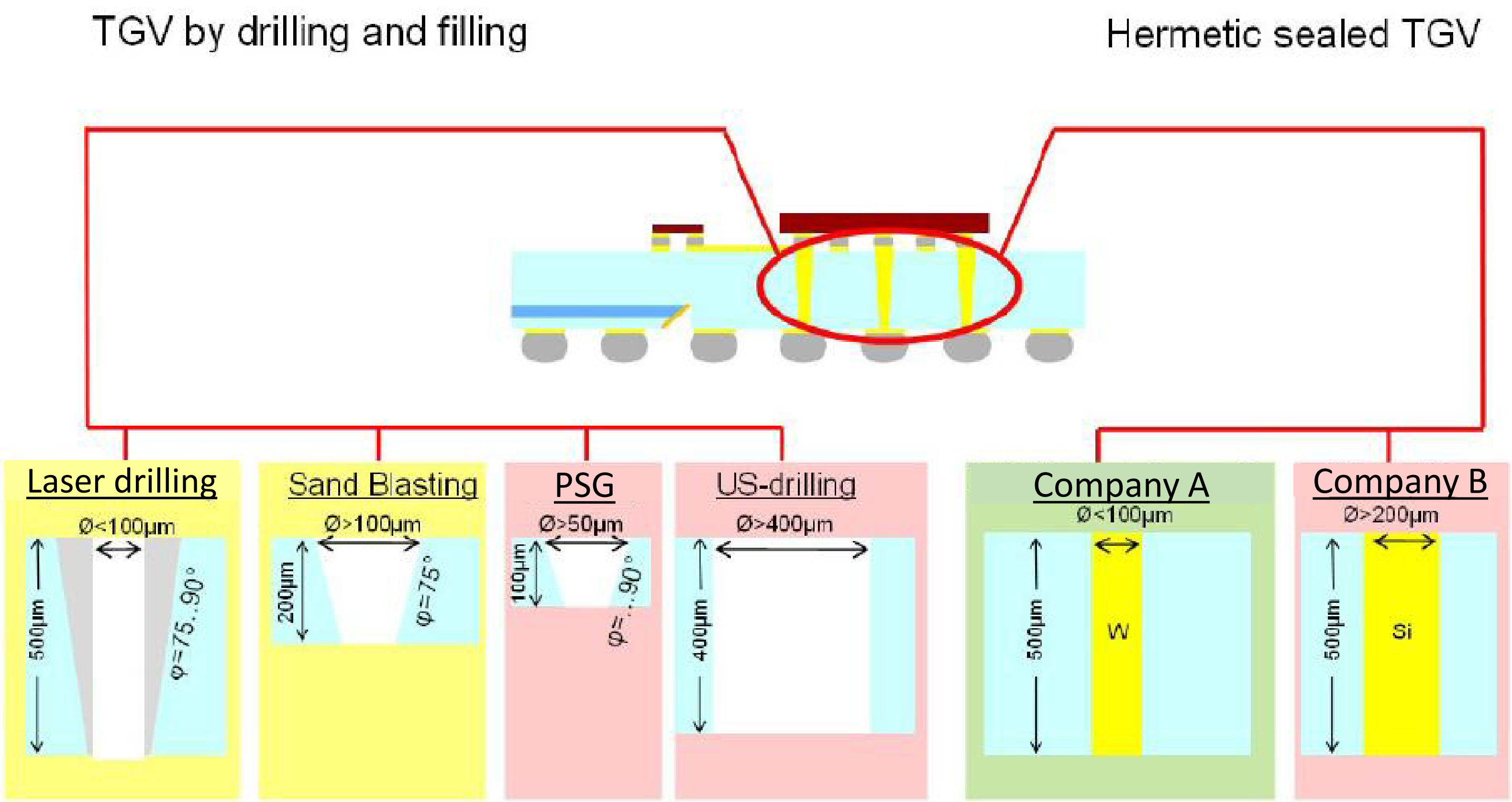


There's now extensive global activity in TGV formation

Through or Blind Vias

- Wet etching & DRIE
- Photo-sensitive glass
- Mechanical drilling
- Laser ablation
- Electrical discharge

Various via processing in glass



Source: Adapted from Ndip, Toepper, Franhoefer IZM,
"Methods for Efficient High-Frequency Modeling and Optimization of Interconnections in Electronic Packaging", ECTC PDC 2012

Through glass vias for RF filters

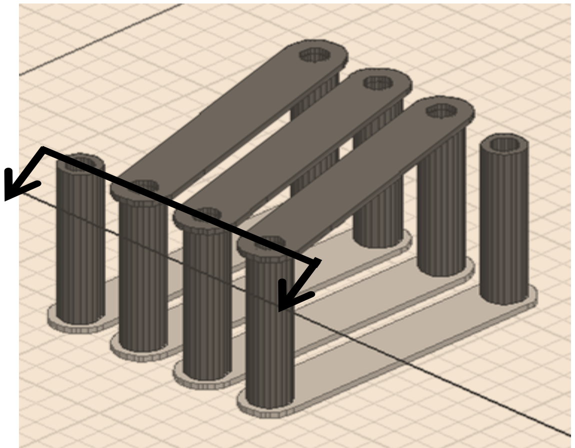
Key customer problems for RF

- Higher data rates and new wireless features are driving the use of higher operating frequencies
- Incumbent materials for RFFE filters have increased loss and non-linearity at these high frequencies
- Customers are faced with a tradeoff between operational efficiency and form factor

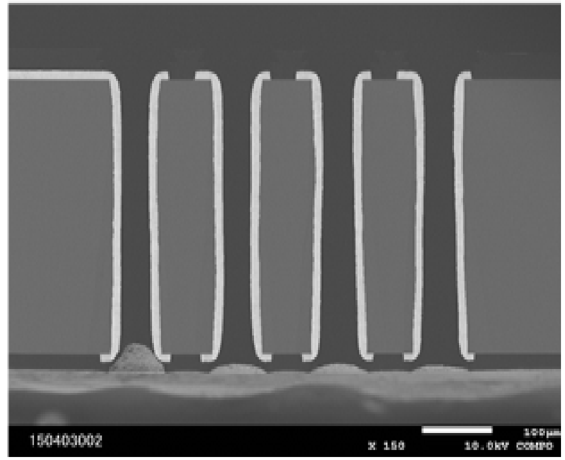
Why glass helps

- Lower RF loss
(up to 80% higher Q value)
→ ***Enables longer battery life***
- Lower non-linearity vs. Si
→***Reduces noise and crosstalk***
- Up to 50% thinner than LTCC and matches Silicon
→ ***Enables thinner devices***

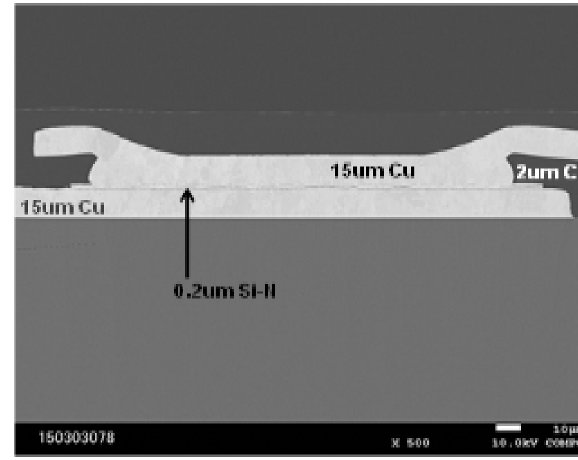
High Q inductors/capacitors have been demonstrated



3D rendering of inductor structure, top-down view

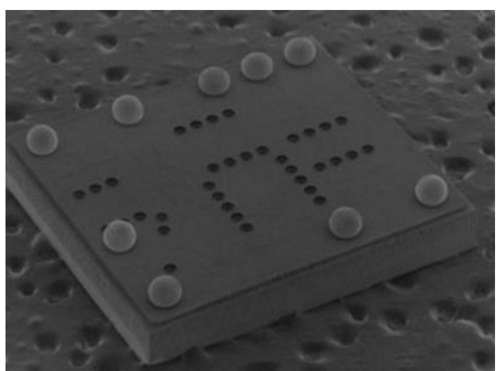


Cross-sectional SEM of a fabricated 3D inductor



Cross-sectional SEM of Cu-Silicon Nitride-Cu MIM structure

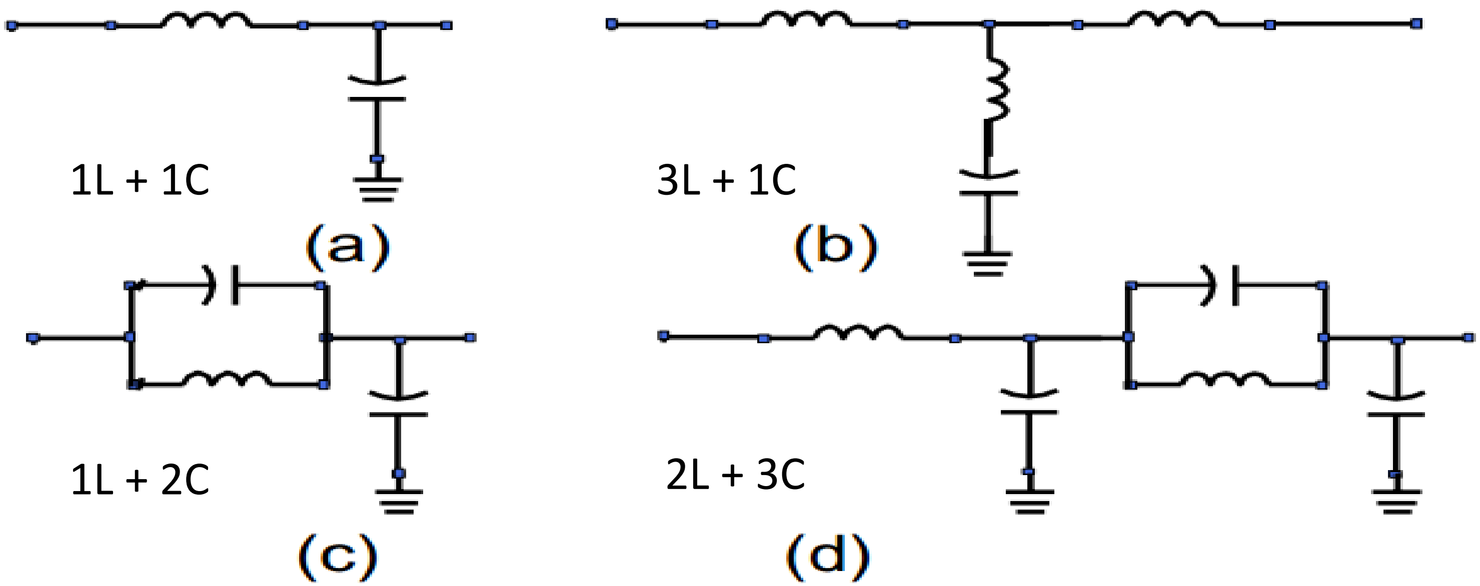
Source: Yun, Kuramochi, Shorey, "Through Glass Via (TGV) Technology for RF Applications", IMAPS 2015, Orlando, FL



- Completed LC Network
- High Q inductance from 3D Solenoid inductor
- Capacitance achieved through MIM structure

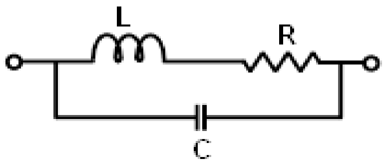
Inductors/capacitors are the building blocks for RF filters

Examples of LC-based low-pass filters:



Source: Yun, Kuramochi, Shorey, "Through Glass Via (TGV) Technology for RF Applications", IMAPS 2015, Orlando, FL

Fundamental understanding of inductor Q factor



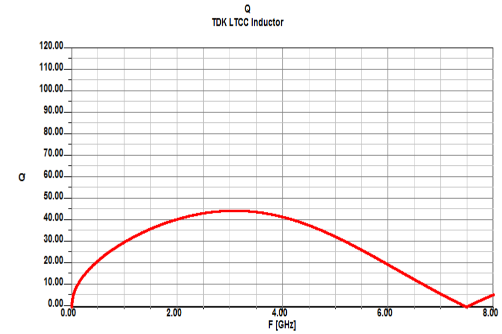
Real inductor equivalent circuit

$$Z = \frac{1}{\left(\frac{1}{R + j\omega L} + j\omega C\right)}$$

Q-factor is defined by $Q \equiv \frac{Im(Z)}{Re\ (Z)}$.

$$\therefore\ Q = \frac{\omega L - \omega^3 L^2 C - \omega C R^2}{R}$$

Negligible



$$\delta_s = \frac{1}{\sqrt{\pi \mu f \sigma}} = \sqrt{\frac{\rho}{\pi \mu f}}$$

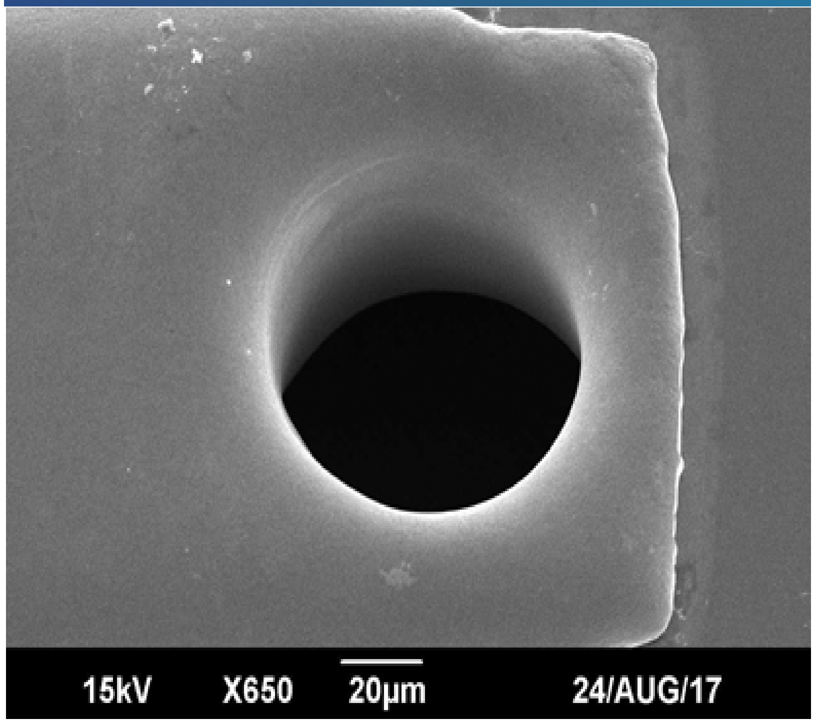
(Skin depth)

R ∝ ρ x (1/δ_s) ∝ $\sqrt{\rho}$

Q ∝ $\frac{1}{\sqrt{\rho}}$ ∝ $\sqrt{\sigma}$

Metal on glass achieves much smoother surfaces

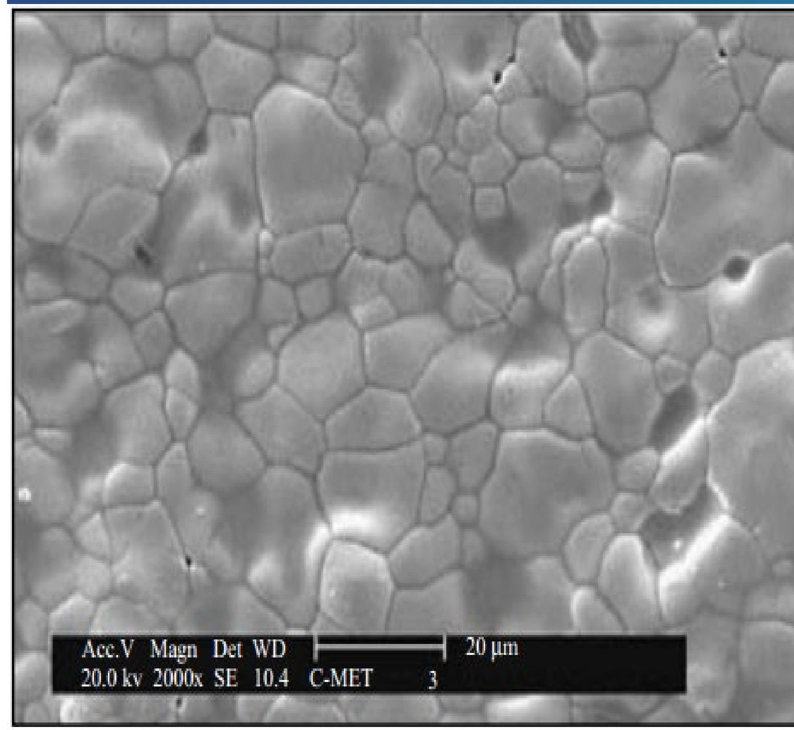
Cu on glass



Source: U. of Florida

Vs.

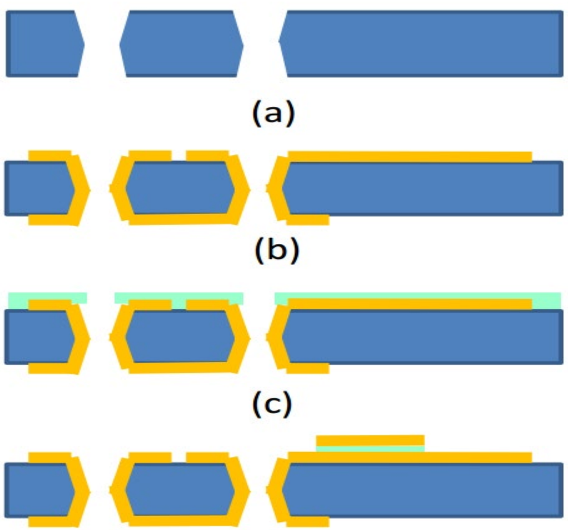
Ag on LTCC



Source: S. Rane et al Soldering and Surface Mount Technology · June 2008

Cu on glass achieves better conductivity than Ag on LTCC

Cu on glass



ρ~1.7uΩ-cm

Ag on LTCC

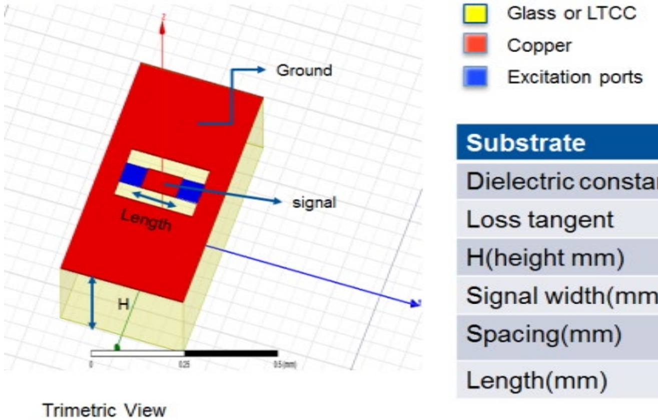
Property	Value
Viscosity, (Pa.s, 10 rpm, 25° C)[1]	180 - 300
Solids, (%)[2]	68.0 - 71.0
Coverage, (cm^2/gram)	80 - 90
Clean-up solvent	1-Propoxy-2 Proponal
Thinner	8250
Line/space resolution, (um, dried)	125 / 125
Dry print thickness, (um)	13 - 18
Fired print thickness, (um)	7 - 10
Resistivity, (mOhms/sq)[3]	</= 5

[1] Brookfield 2xHAT, SC4-14 / 6R spindle and utility cup
[2] 750° C
[3] Normalized to 15 um dry thickness

ρ~2.5-4uΩ-cm

Smoother, more conductive metal leads to lower loss

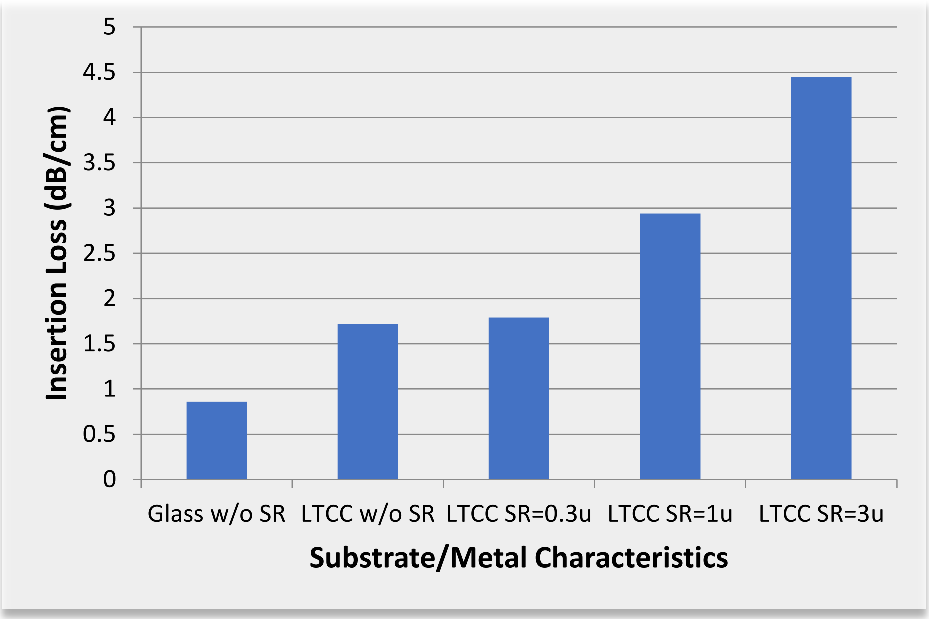
HFSS modeling of losses at 2.8GHz



Substrate	Glass/LTCC
Dielectric constant	5.5/9.8
Loss tangent	0.0058
H(height mm)	0.1
Signal width(mm)	0.0625
Spacing(mm)	0.0115/0.0259
Length(mm)	0.1

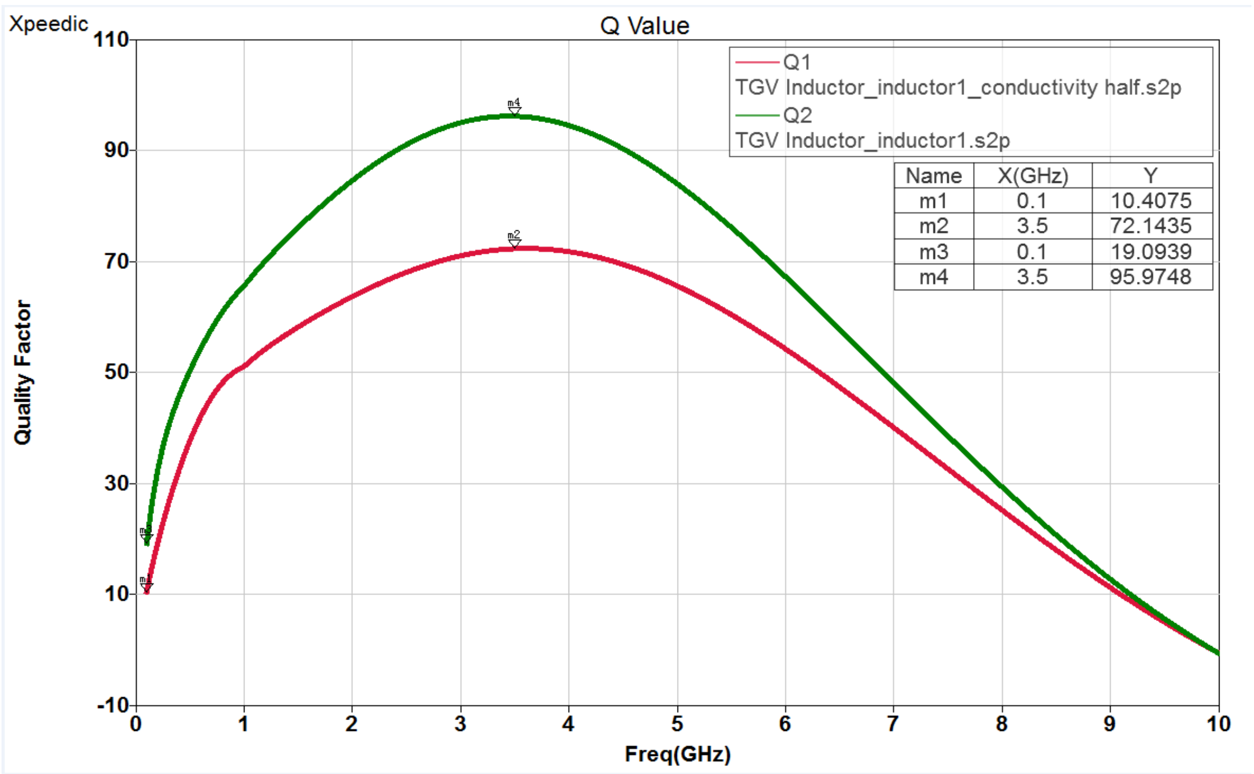
Cu/glass resistivity: 1.7 uΩ-cm
Ag/LTCC resistivity: 4.2 uΩ-cm

1cm Transmission Line Insertion Loss



Source: U. Florida

Higher conductivity → Higher Q: HFSS TGV simulation



$$Q \propto \frac{1}{\sqrt{\rho}} \propto \sqrt{\sigma}$$

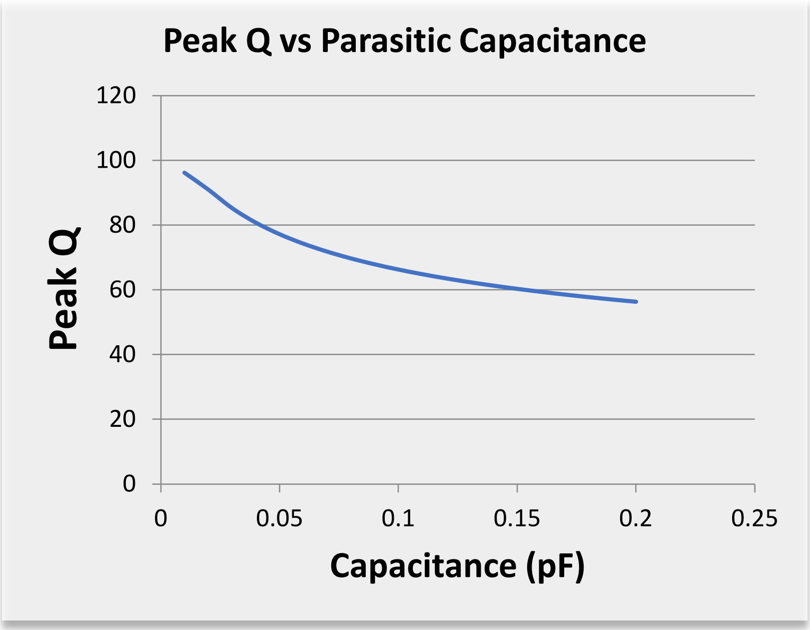
50% σ → 70% Q

Source: Xpeedic

Parasitic capacitance reduces inductor Q-factor

$$Q = \frac{\omega L - \omega^3 L^2 C - \omega C R^2}{R}$$

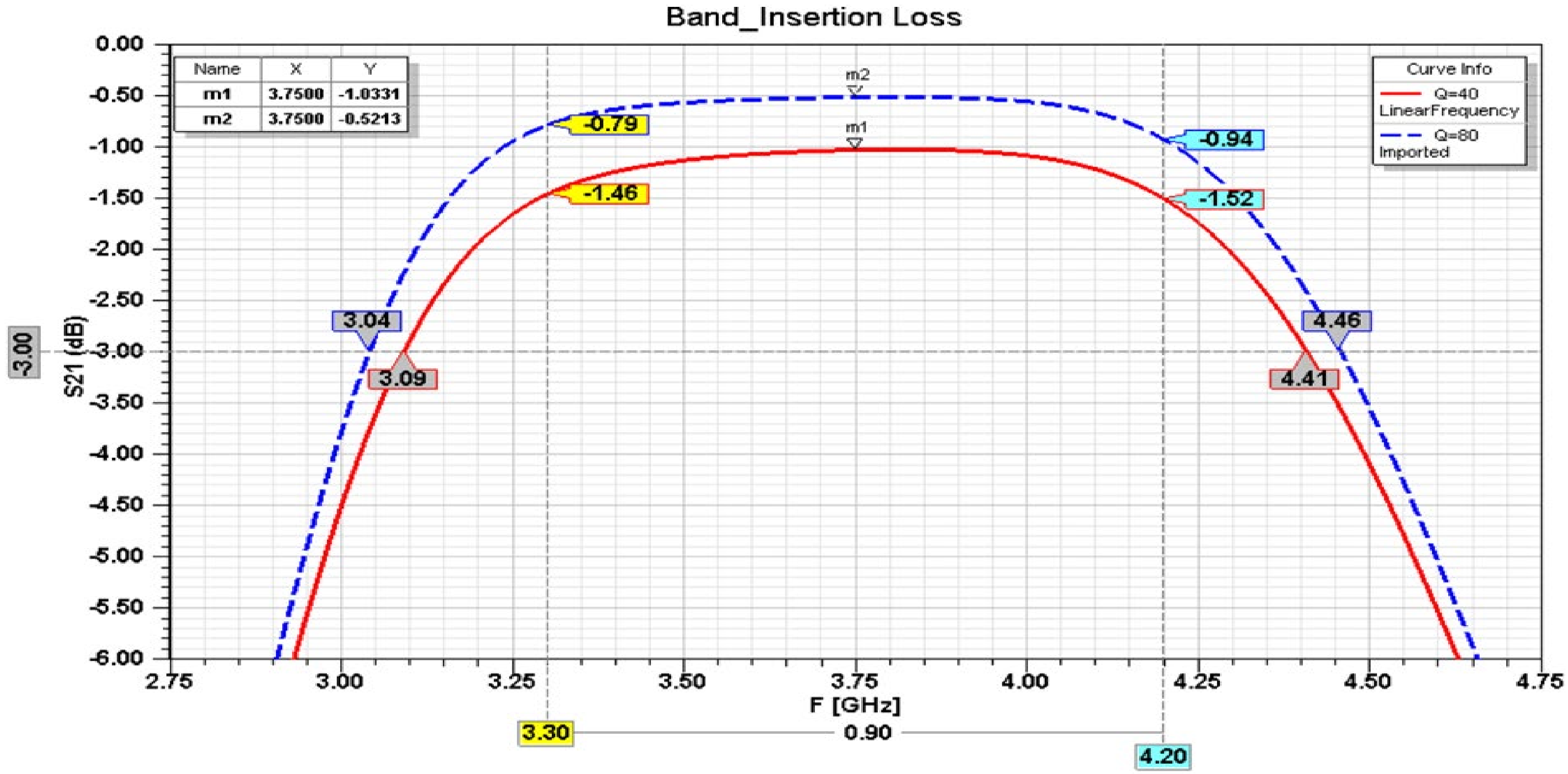
Peak Q can be obtained by taking dQ/dω = 0



L should be designed with the lowest possible parasitic capacitance:

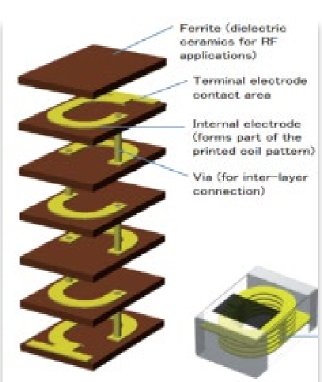
- Electrode shape/orientation (TGV advantaged)
- Dielectric constant (glass 3.7-6 vs. LTCC 6-10)

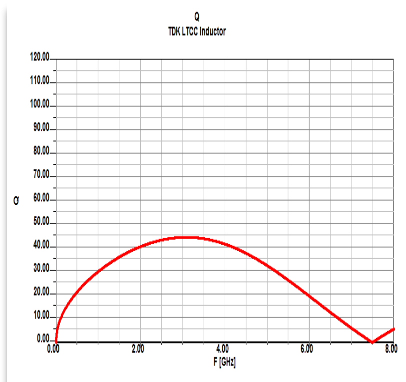
Higher Q results in lower insertion loss in 5G bands



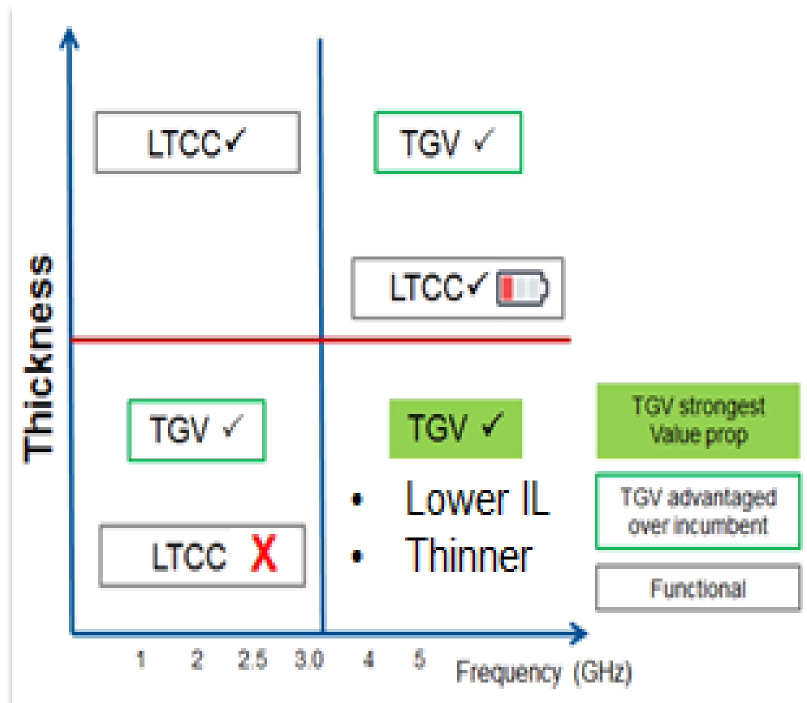
Diplexer example:
Thinner with lower insertion loss vs. LTCC

LTCC

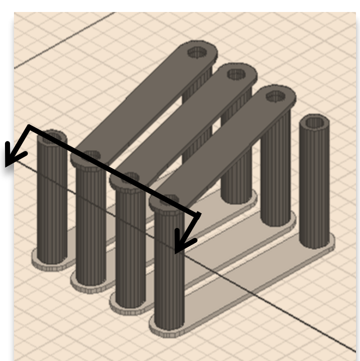


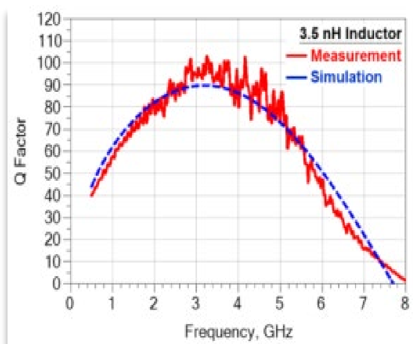


Source: TDK inductor library and article "High-Precision Multilayering Technology Combines Small Size and High-Q Rating" by TDK



TGV

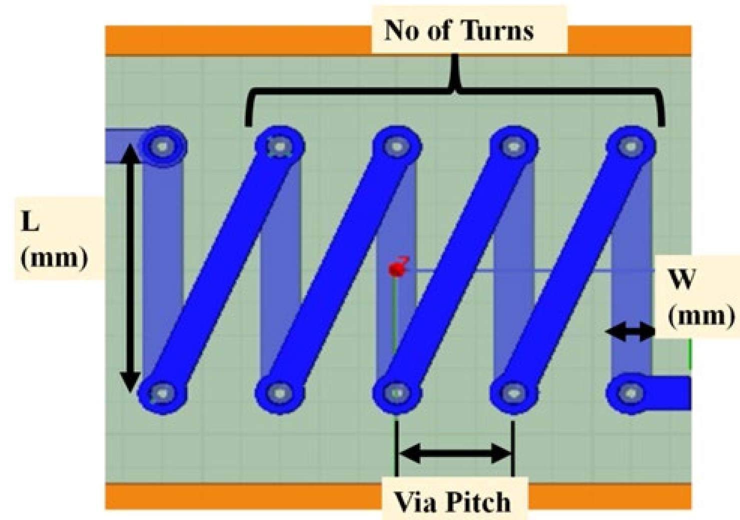


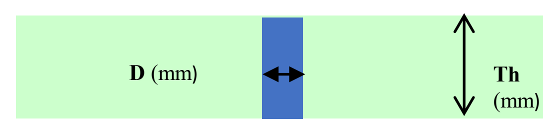


Source: ASE "Glass Based 3D-IPD Integrated RF ASIC in WLCSP", 2017 IEEE ECTC

Summary of regression analysis: How to maximize Q?

TGV parameter	Direction for higher Q
Metal conductivity	↑
Number of turns	↓
Via f and metal width	↑
Inductor arm length	↓
Glass thickness	↑
Via pitch	no impact





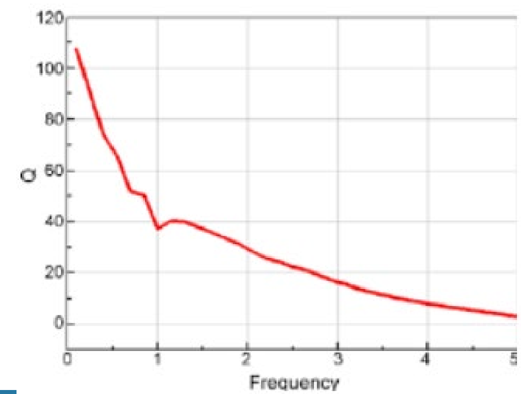
Fundamental understanding and demo of capacitor Q

$$Z_C = Z + R_{ESR} = \frac{1}{j\omega C} + R_{ESR}$$

Real capacitor equivalent circuit

Q-factor is defined by $Q \equiv \frac{Im(Z)}{Re\ (Z)}$.

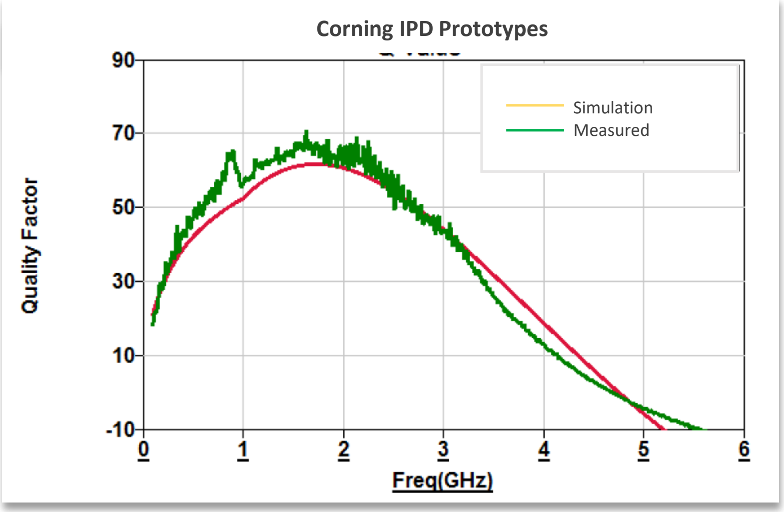
$$\therefore Q = \frac{1}{\omega C R_{ESR}}$$

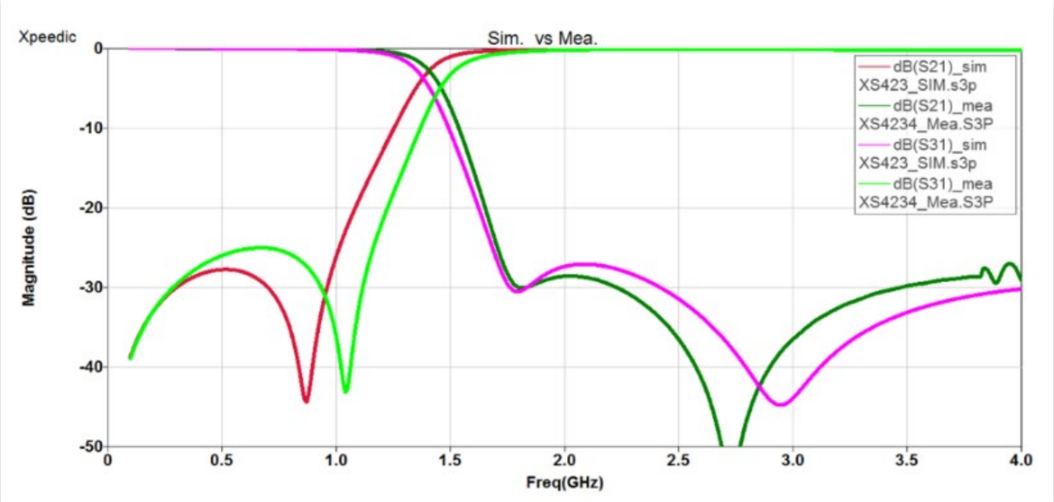


Higher conductivity and smoother metal will deliver higher Q factor

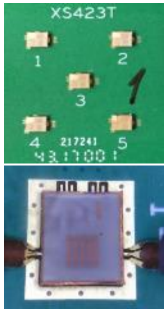
- Q>560 (10pF @ 2GHz) demonstrated with TGV

TGV IPD prototypes show high Q and low capacitance, which validates Corning's model



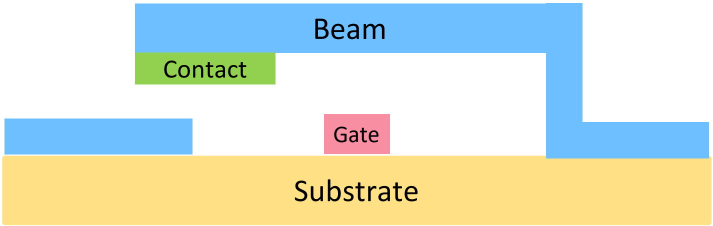


Source: Xpeedic



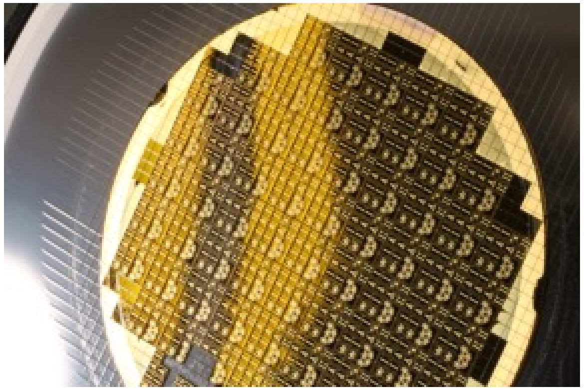
- First TGV IPD prototype designed at sub-3 GHz shows higher Q (peak 70) vs. Si (peak 60) → Next, we are developing sub-7 GHz bandpass filter
- Developed knowledge in TGV and metallization processes with fab partners

Menlo DMS Technology for RF



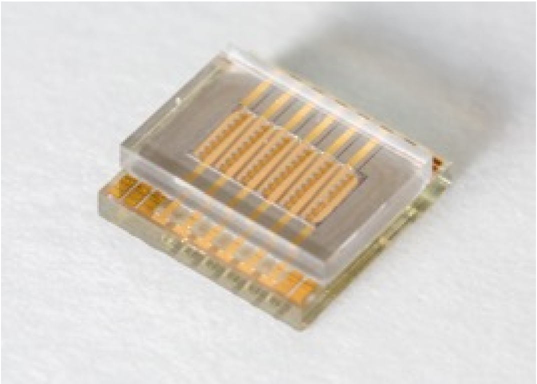
Menlo's DMS, or digital-micro-switch, is an ideal material set and processing platform for high-performance RF products

Wafer-scale manufacturing on glass substrates



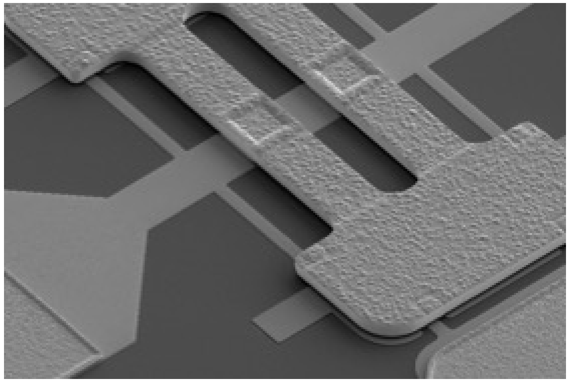
(4" to 8")

Hermetically sealed RF switches in air cavity glass package



(1mm^2 to 25mm^2)

DMS unit cell (our "mechanical transistor")



(50um x 50um)

High-Reliability

- Shipping in production to a >3B cycles spec with roadmap to >20B
- Hot-switch capable

Low-cost roadmap

- Simple switch design can be made very small (50µm x 50µm)
- TGV packaging for smallest die-size
- Only 14-step, scalable manufacturing process

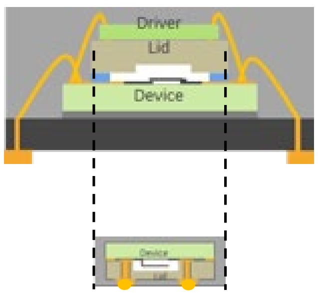
RF Integration platform

- Metal-on-glass processing can be integrated with passives, filters, etc.

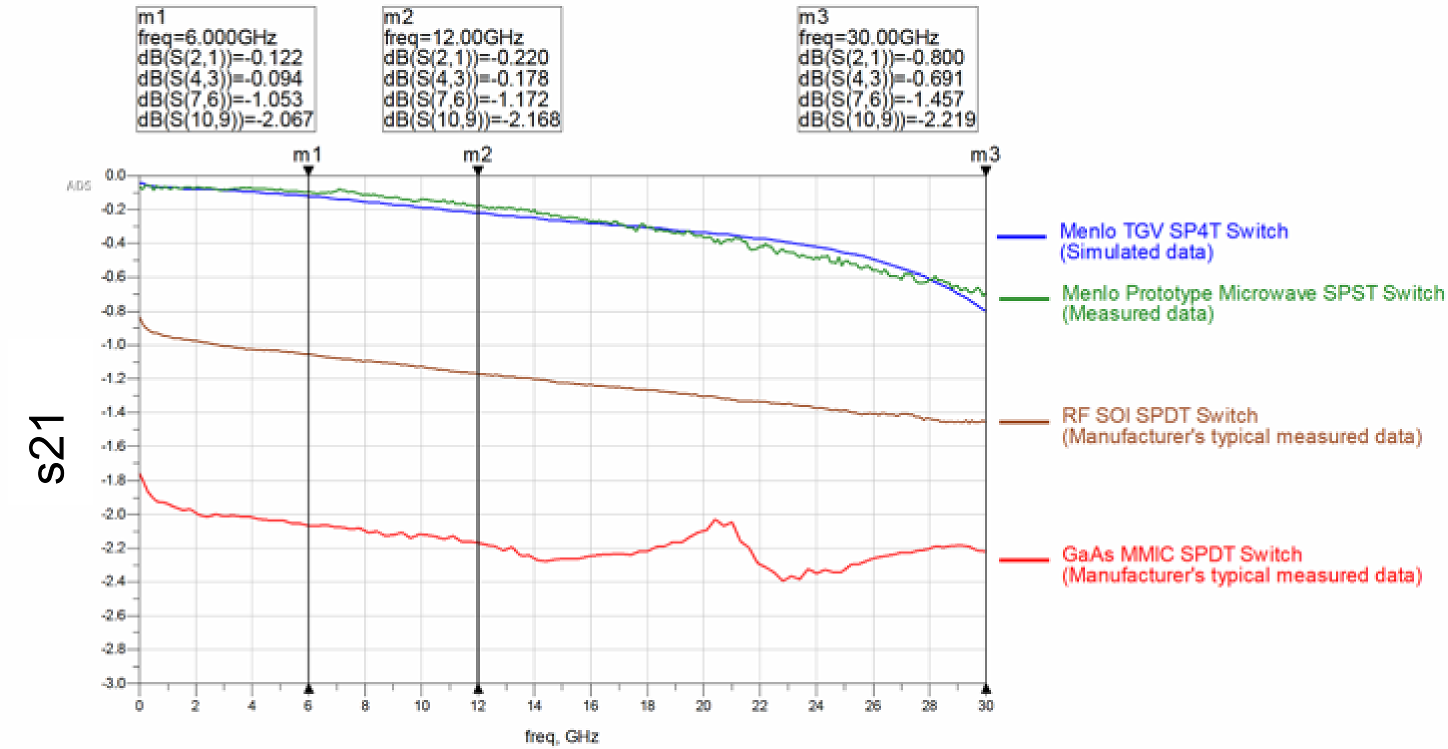
From DC to mmWave

Advances in packaging will enable DMS products to achieve much higher BW

MM3100
WL Glass Cap
in **6x6mm** QFN



WL Glass Cap
w/TGV CSP

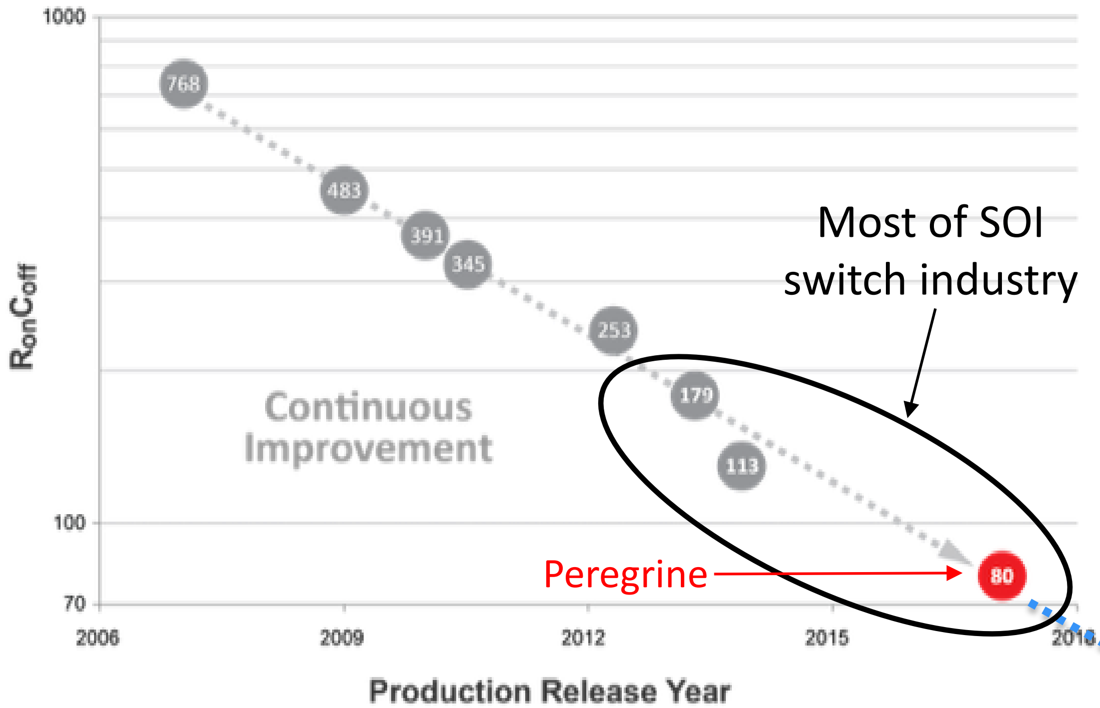


With TGV, everything gets better from RF point of view:

- Lower parasitics, lower bulk resistance/IL
- Improved thermals, better power handling

Initial measurements of DMS unit cell show mmWave performance is achievable

RonCoff comparison of DMS technology



- For SOI, RonCoff is measured for ***single transistor***
- Actual switch product uses transistor stacks (up to 20!) for up to 80V

~10fs

- Menlo DMS requires only "stack of 1" for 200V voltage handling
- MM3100 RonCoff = 40fs, <10fs with TGV for 2018
- Glass is ultimate substrate platform for high RF linearity, >90dBm IP3

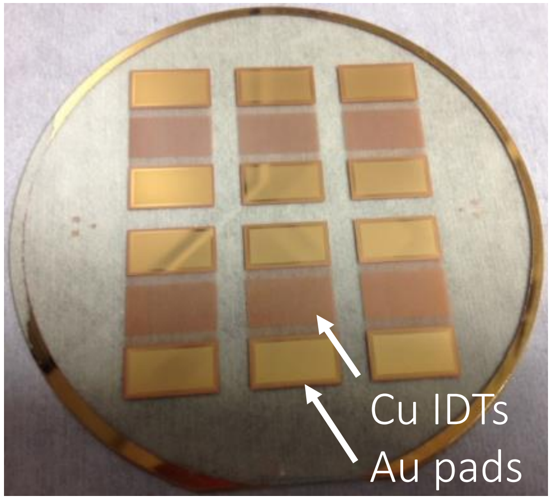
menlo micro

Through Glass Vias (TGVs): HAST Testing

HAST Testing

- HAST testing used to test reliability of biased, closely spaced routing metal lines on glass of differing composition
- HAST test conditions: 130 C, 85% RH, 2 atm, 5 V DC bias, 96 hrs

Wafer Types for HAST Testing
SG 3
SG 8
SG 8 with 1 µm PECVD Si_3N_4
Fused silica
Si with 3 kA thermal SiO_2

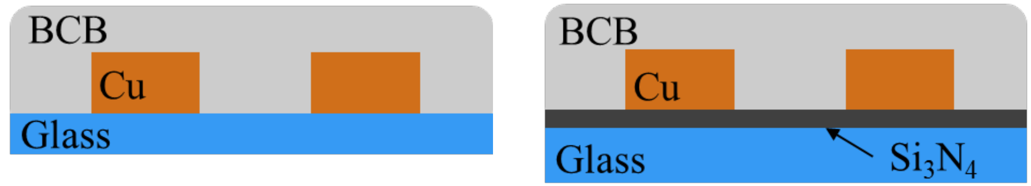


Glass wafer with Cu IDTs for HAST testing

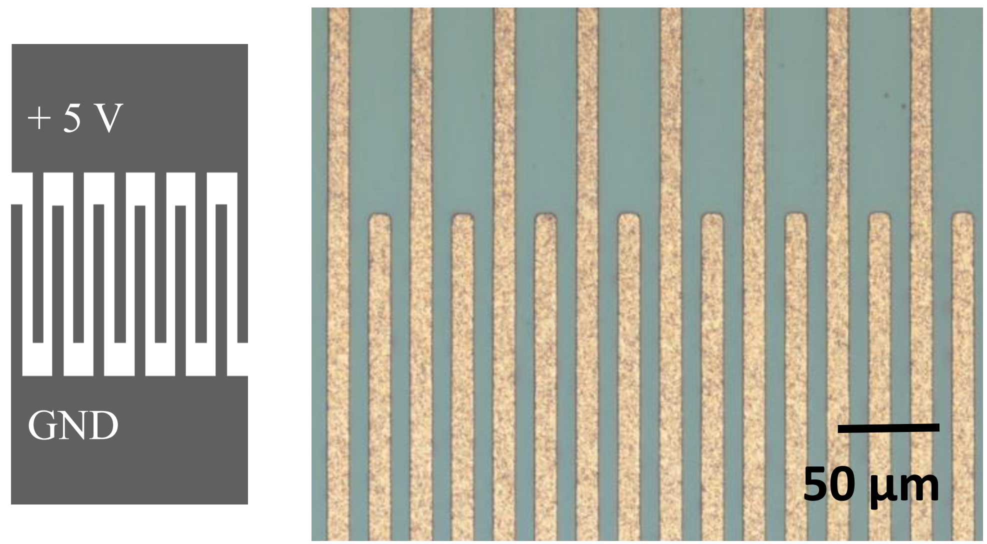
HAST Testing: Experimental plan

Interdigitated Test Structures

- Electroplated Cu lines on Ti/Cu sputtered seed layer
- 10 µm line/space
- 400 fingers each with 9 mm of overlap (3.6 m total length)
- Passivated with 5 µm of BCB

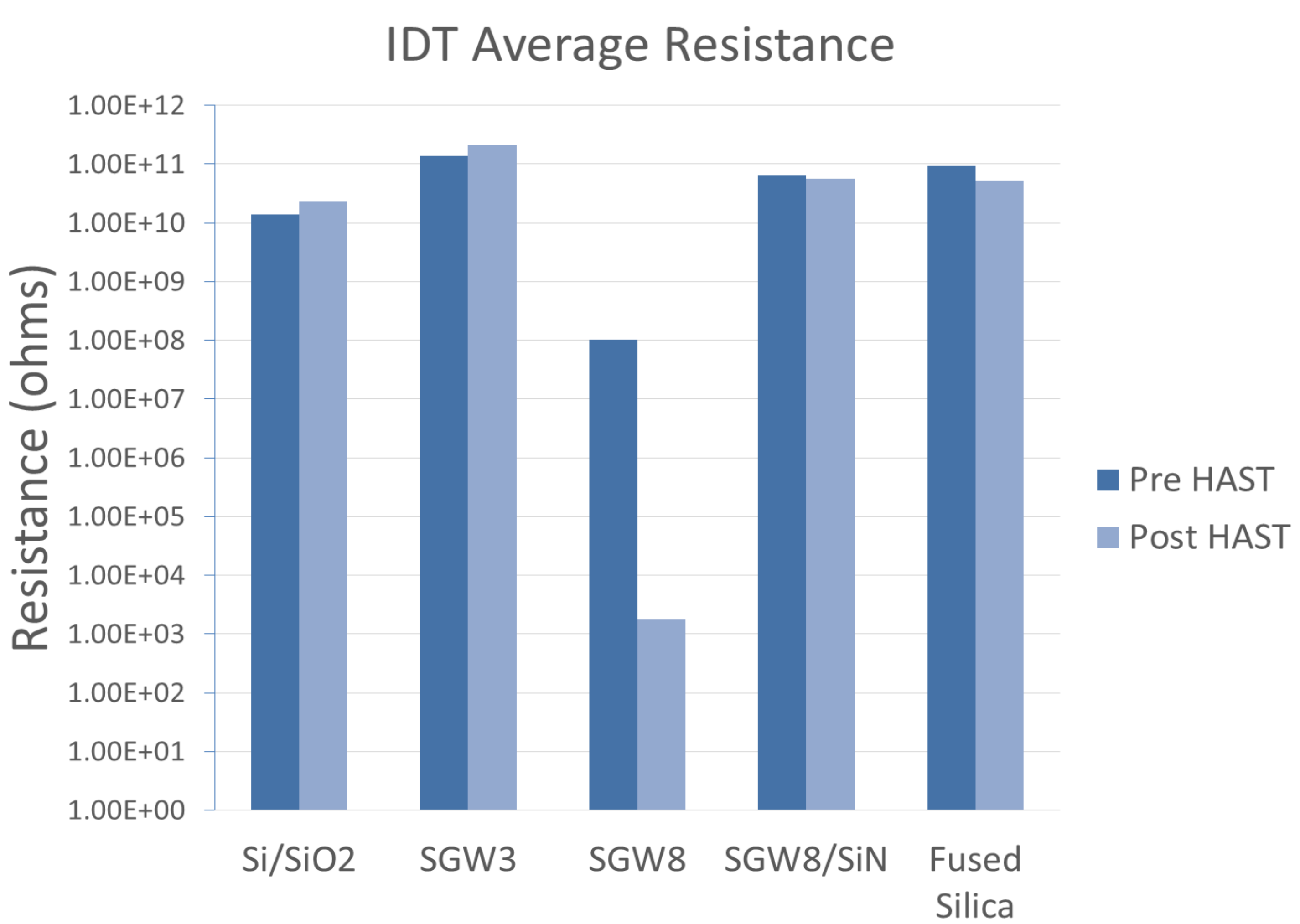


Cross section view of interdigitated test structure (IDT) with and without silicon nitride barrier layer



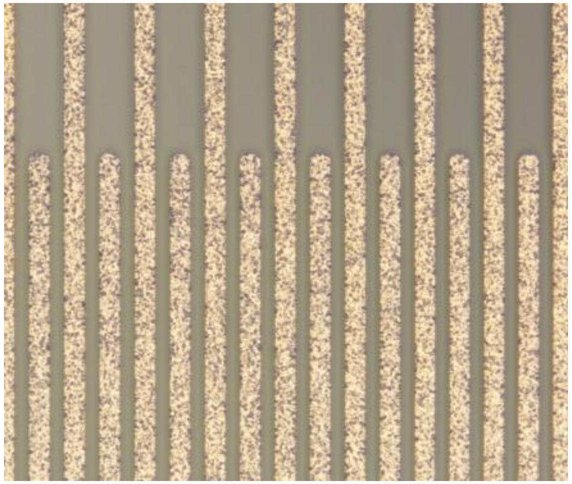
Layout and microscope image of interdigitated test structure (IDT)

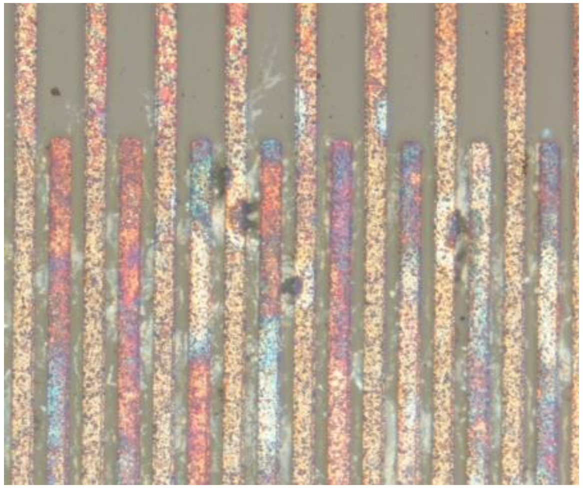
HAST Testing – IDT Isolation Results



HAST Testing: Optical inspection

SG 3

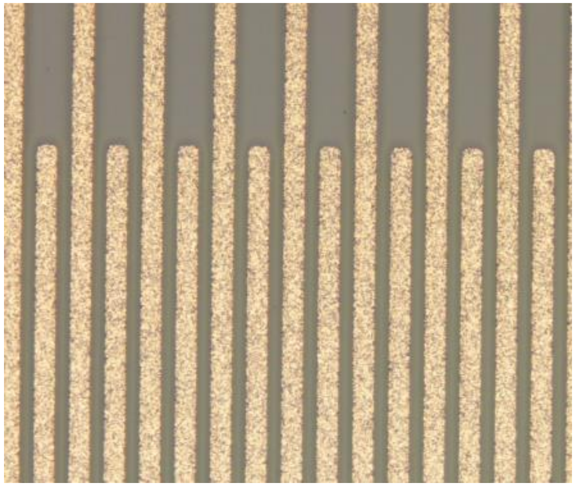


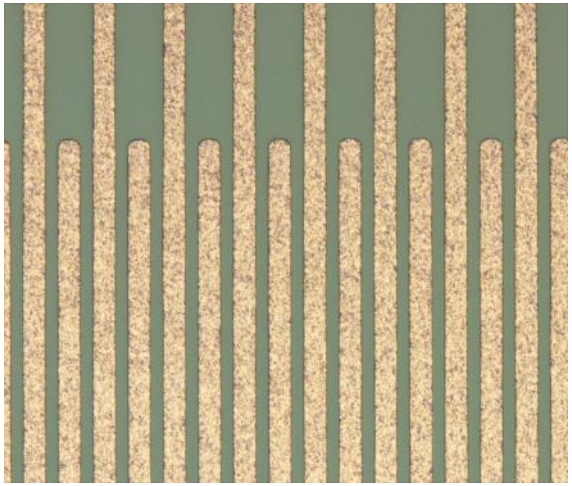


SG 8

Unbiased test sites did not exhibit degradation

HPFS® Fused Silica





SG 8, 1 µm Si_3N_4

Quiz

1. What are 2 properties of glass that make it an excellent material for electronic applications?

2. What glass application is used to reduce silicon die thickness for mobile devices?

3. What are the 3 key levers to reduce in-process warp in fan-out packaging?

Thank You

For more information, contact:

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- Dr. Jay Zhang – zhangjj@corning.com

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Precision Glass Solutions

JOIN US FOR AN INFORMAL COCKTAIL HOUR

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OF OUR *2ND ANNUAL*

Corning Leadership in Glass Award

When: Wednesday, 6-8PM

Where: Condesa 2 Room, The Cosmopolitan

What: Drinks, appetizers, and networking

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Credit/Acknowledgement

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- ITRI
- RTI International/Micross Components
- Georgia Tech
- Univ. of Florida: Prof. PK Yoon, Renuka Bowrothu
- Xpeedic: Lijun Chen, Feng Ling
- Menlo Microsystems: Chris Giovanniello, Chris Keimel