Материалы для производства полупроводников ULE, TSG, HPFS

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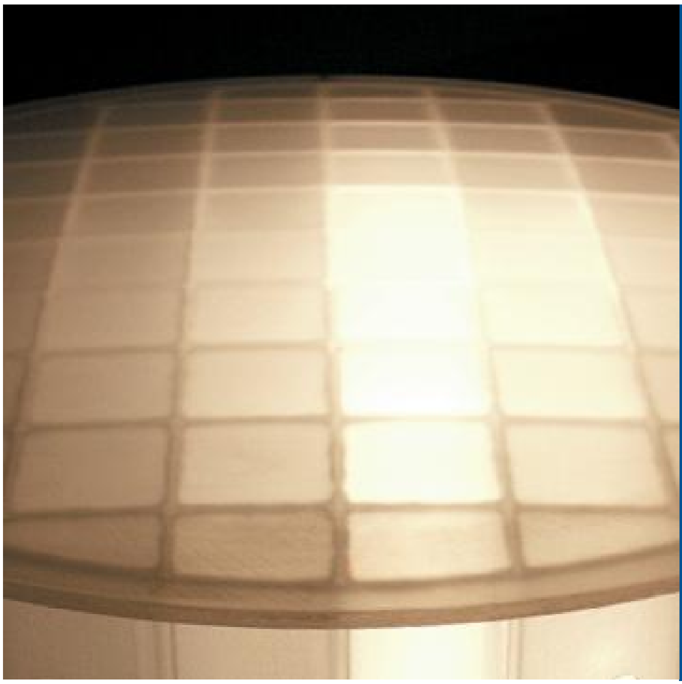
ULE® Corning Code 7972
Ultra Low Expansion Glass
Advanced Optics and Materials



ULE® Corning Code 7972 Ultra Low Expansion Glass is a titania silicate glass with unique characteristics that have made it the material of choice in applications ranging from machine tool reference blocks to solid and lightweight mirror blanks for large astronomical telescopes and space satellite applications. It is formed as 1.5-meter boules from which virtually any size or shape product can be made.

Near Zero Thermal Expansion *is the key attribute for which system designers specify Corning ULE®. This material offers superior dimensional stability ~*

- ❖ *Coefficient of thermal expansion (CTE) is nominally zero at room temperature*
- ❖ *Expansivity can be adjusted to provide zero CTE at other temperatures when needed for specific applications*
- ❖ *High homogeneity of CTE within boules enables efficient material utilization*
- ❖ *CTE is nondestructively measured on all ULE® boules, enabling precision engineering and analysis of the thermal response of products in the end use environment*

Fabrication Flexibility *is the key to product design freedom. Corning utilizes several key manufacturing processes which enable the production of a variety of products ~*

- ❖ *Monolithic solids from a few centimeters to over 8 meters in diameter*
- ❖ *Lightweight fusion bonded structures offering up to 80% weight reduction over the same sized solid*
- ❖ *Ultralightweight frit bonded structures with up to 95% weight reduction are possible using a proprietary glass ceramic frit designed to closely match the thermal expansion of ULE® glass.*

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CTE Variation and Inclusion Quality Grades

Mean Linear Coefficient of Thermal Expansion (CTE)

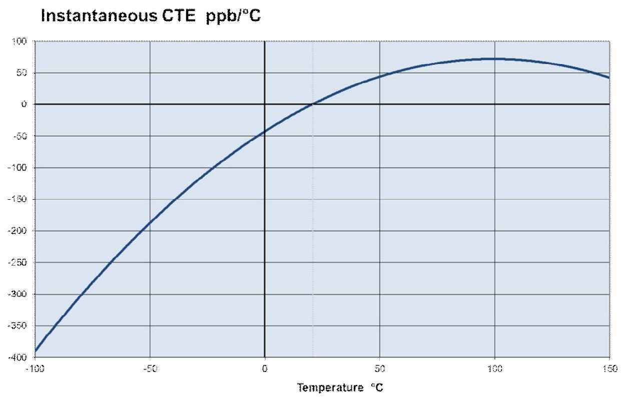
The guaranteed maximum limits for the mean linear CTE are as follows:

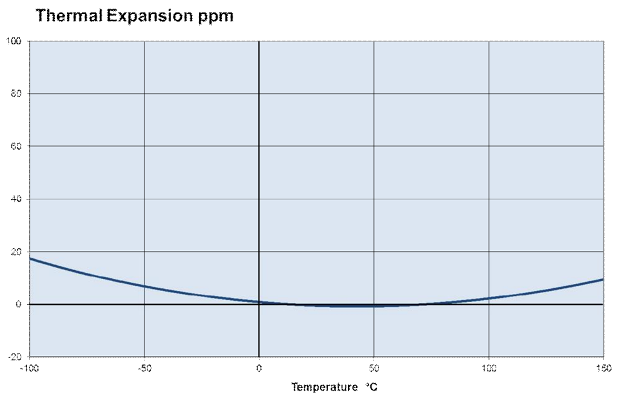
The mean linear CTE shall be **0 ± 30 ppb/°C** from 5°C to 35°C with a 95% confidence level.

Quality Grade Selection Chart

	Maximum CTE Variation (ppb/°C)		Optical Retardation	Inclusions	*Special grades and sizes available on request*	
Grade	**Radial Range**	**Axial Range**	**Birefringence (nm/cm)**	**Inclusion Quality**	**Diameter < 20"**	**Diameter 20" to 56"**
Premium Grade	10	10	10	Inclusion max mean diameter: Inclusions per cubic inch: Avg. no. of inclusions per cu. in.:	0.040" 4 0.1	N/A
Mirror Grade	15	15	20	**Critical Zone:** Inclusion max mean diameter: Inclusions per cubic inch: Avg. no. of inclusions per cu. in.:	0.040" 4 0.1	0.080" 6 0.2
				Non-Critical Zone: Inclusion max mean diameter: Inclusions per cubic inch: Avg. no. of inclusions per cu. in.:	0.100" N/S 0.2	0.250" N/S 0.6
Standard Grade	15	15	20	Inclusion max mean diameter : Inclusions per cubic inch: Avg. no. of inclusions per cu. in.:	0.100" N/S 0.2	0.250" N/S 0.6
Tooling Grade	N/A	N/A	N/A	N/A	Contact Corning for availability.	

- CTE verification is performed using a non-destructive ultrasonic method.
- Excellent long term dimensional stability is exhibited at room temperature. No residual figure change is observed when taking an optic from 350°C to water quench.
- There has been no measurable delayed elastic effect. This is an important consideration when large strain is present during fabrication or when environmental loading is present, such as during gravity release or dynamic control of active optics.
- No measurable hysteresis results from thermal cycling.





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Thermal Properties

Mean Linear Coefficient of Thermal Expansion 5°C to 35°C (α)	$0 \pm 30 \times 10^{-9}$/K [0 ± 30 ppb/°C]	Mean Specific Heat (C_p)	767 J/(kg * °C) [0.183 cal/(g * °C)]
Thermal Conductivity (K)	1.31 w/(m * °C) [1.13 kcal/(m * h * °C)]	Strain Point	890°C [1634°F]
Thermal Diffusivity (D)	0.0079 cm^2/s	Annealing Point	1000°C [1832°F]
D.C. Volume Resistivity, 200°C 100Hz (R)	$10^{11.6}$ ohm * cm	Softening Point (estimated)	1490°C [2714°F]

Mechanical Properties

Poisson's Ratio (v)	0.17	Specific Stiffness (E/ρ)	3.12×10^6 m [1.23×10^8 in]
Ultimate Tensile Stress (MOR)	49.8 MPa [7220 psi]	Shear Modulus (G)	29.0 GPa [4.20×10^6 psi]
Knoop Hardness, 200g load	460 kg/mm^2	Bulk Modulus (K)	34.1 GPa [4.95×10^6 psi]
Density (ρ)	2.21 g/cm^3 [0.079 lb/in^3]	Elastic Modulus (E)	67.6 GPa [9.80×10^6 psi]

Optical Properties

Stress Optical Coefficient	4.15 (nm/cm)/(kg/cm^2) [0.292 (nm/cm)/psi]	Abbé Number (v_d)	53.1
Refractive index (nominal CTE Material)	n_F (486 nm) 1.4892 n_D (589 nm) 1.4828 n_C (656 nm) 1.4801	dn/dt	20-40°C 10.68×10^{-6}/°C 40-60°C 11.24×10^{-6}/°C

Chemical Durability

- Excellent resistance to weathering
- Exhibits virtually no surface clouding or electrical surface leakage when subjected to attack by water, sulfur dioxide, and other atmospheric gases.
- High resistance to attack by nearly all chemical agents.

Solution at 95°C	**Test Duration**	**Weight Loss** mg/cm^2
5% HCl	24h	< 0.01
5% NaOH	6h	0.9
0.02N Na_2CO_3	6h	0.02
5% H_2SO_4	24h	< 0.01
H_2O	24h	< 0.01

Unless otherwise stated, all values @ 25°C

Corning ULE® 7973

7973 is a titania-silicate low expansion glass that has been tailored to meet the needs for mask and optical substrates for EUVL applications. 7973 has a similar composition to ULE® 7972 glass and is made using the same flame deposition process. The lithography transition from 193nm to 13.4nm required a major design shift in stepper optics from refractive to reflective. In reflective optics, substrate materials should be purely passive. The incident light should reflect off of the multilayer coatings of the optics and the photomask without the introduction of any mechanical or optical distortion caused by the underlying substrate. To minimize distortion from the minute temperature changes and meet the stringent EUVL specifications, the substrates must have a near-zero coefficient of thermal expansion (CTE) and tightly controlled zero cross over range. The extremely low CTE requirements are specified in parts per billion per degree Celsius (ppb/C).

Quality Grade Selection Chart 7973 EUV

Grade	Inclusion Quality	Blank Dimensions (Diameter or Diagonal)	
		< 20″ (< 508 mm)	20 - 58″ (508 - 1473 mm)
EUV Grades	Critical Zone: Total Inclusion Cross Section: ≤ 0.03 mm^2/100cc Maximum Inclusion Size: 0.1 mm		
	Non-Critical Zone: Total Inclusion Cross Section: ≤ 2.00 mm^2/100cc Maximum Inclusion Size: 1.27 mm		
EUV Mask A Grade	No visible inclusions > 0.05 mm		

Notes:
- Critical Zone — a quality layer typically extending to a depth of 0.200″ (5 mm) below the surface specified by the customer for finishing.
- Non-Critical Zone — all glass outside the critical zone
- Inclusions with 0.005″ (0.13 mm)or smaller mean diameter are disregarded.
- Mirror and standard grades are available in sizes up to 58″ (1473 mm) diameter

7973 Summary of Key Attributes

Attribute	7973 Premium Grade	7973 Mirror Grade	7973 Standard Grade	7973 Tooling Grade	7973 EUV Premium Grade	7973 EUV Standard Grade	7973 EUV Mask A Grade
No visible inclusions > 0.05 mm							■
Low Birefringence	■				■	■	■
Low Radial CTE Range	■				■		■
Low Axial CTE Range	■				■		■
Tzc specified					■	■	■
Low Striae					■	■	■
Low Inclusions in CZ		■			■	■	■
Available in larger sizes (up to 58″ diameter)		■	■				
Economical (No certification of any properties)				■			

Quality Grade Selection Chart 7973

Grade	Inclusion Quality	Blank Dimensions (Diameter or Diagonal)	
		< 20″ (< 508 mm)	20 - 58″ (508 - 1473 mm)
Premium	Max. Mean Diameter	0.040″ (1 mm)	N/A
	No./Cu. Inch	4	
	Avg. No./Cu. Inch	0.1	
Mirror	Critical Zone:		
	Max. Mean Diameter	0.040″ (1 mm)	0.080″ (2 mm)
	No./Cu. Inch (No./mm^3)	4 (2.4×10^{-4})	6 (3.7×10^{-4})
	Avg. No./Cu. Inch (Avg. No./mm^3)	0.1 (6.1×10^{-6})	0.2 (1.2×10^{-5})
	Non-Critical Zone:		
	Max. Mean Diameter	0.100″ (2.5 mm)	0.250″ (6.4 mm)
	No./Cu. Inch (No./mm^3)	N/S	N/S
	Avg. No./Cu. Inch (Avg. No./mm^3)	0.2 (1.2×10^{-5})	0.6 (3.7×10^{-5})
Standard	Max. Mean Diameter	0.100″ (2.5 mm)	0.250″ (6.4 mm)
	No./Cu. Inch	N/S	N/S
	Avg. No./Cu. Inch (Avg. No./mm^3)	0.2 (1.2×10^{-5})	0.6 (3.7×10^{-5})
Tooling	N/A	N/A	N/A

Optical and Thermal Properties

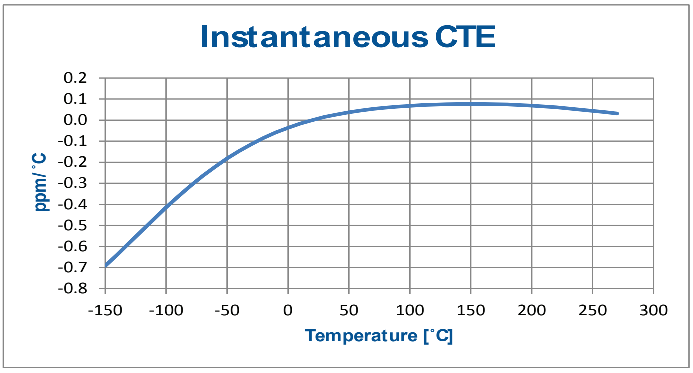
Glass Code	Striae	Optical Retardation	CTE Zero Cross Over Temperature	Coefficient of Thermal Expansion (CTE) Range	
	0 to 400 Scale [%]	Birefringence [nm/cm] maximum	T_{zc} [˚C]	Radial [ppb/ ˚C]	Axial [ppb/ ˚C]
7973 Premium Grade	100	10	See note below*	≤ 10	≤ 10
7973 Mirror Grade	100	20	See note below*	≤ 15	≤ 15
7973 Standard Grade	100	20	See note below*	≤ 15	≤ 15
7973 Tooling Grade	NS	NS	See note below*	≤ 100	≤ 100
7973 EUV Premium Grade	Critical Zone: 50 Non-Critical Zone: 100	10	User defined within 15 ˚C to 32 ˚C ± 5 °C	≤ 10	≤ 10
7973 EUV Standard Grade	Critical Zone: 50 Non-Critical Zone: 100	20	20 ºC ± 10 °C	≤ 15	≤ 15
7973 Mask A Grade	50	NS	20 ºC ± 3 °C	≤ 6	N/A

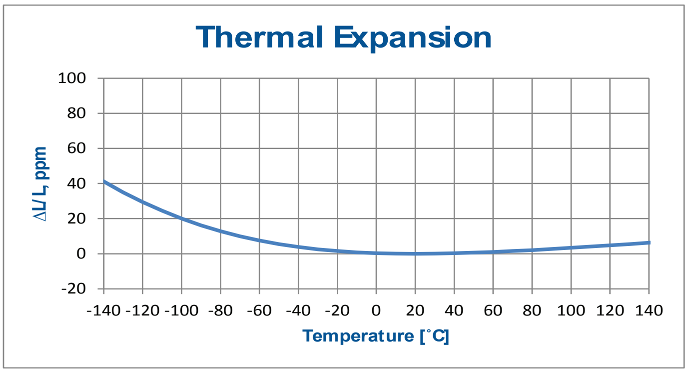
Note:
* Linear Coefficient of Thermal Expansion - The mean CTE shall be 0 ± 30 ppb/°C from 5 °C to 35 °C with a 95% confidence level and 0 ± 100 ppb/°C from 5 °C to 35 °C for Tooling Grade

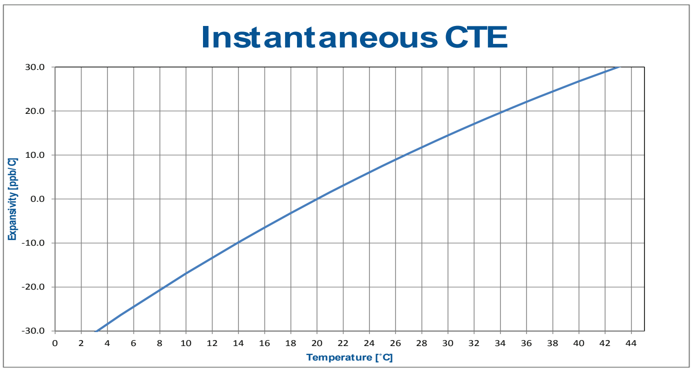
Stress Optical Coefficient	4.15 (nm/cm)/(kg/cm^2)
Striae Normal to Blank Faces	None
Abbé Constant	53.1
D.C. Volume Resistivity, 200 ˚C 100 Hz (R)	$10^{11.6}$ ohm•cm
Thermal Conductivity (K)	1.31 W/(m•K)
Unless otherwise stated, all values above @ 25 °C	

Thermal Diffusivity (D)	0.0079 cm^2/s
Mean Specific Heat (C_p)	767 J/(kg•˚C)
Strain Point	890 ˚C
Annealing Point	1000 ˚C
Softening Point (estimated)	1490 ˚C
Unless otherwise stated, all values above @ 25 °C	

Expansivity







- CTE verification is achieved through a non-destructive ultrasonic method.
- Stability: Excellent long term dimensional stability at room temperature. No residual figure change when taking a blank from 350 ˚C to water quench.
- Delayed elastic effect: There has been no measurable delayed elastic effect in Corning 7973. This is an important consideration when large strain is present during fabrication or when environment loading is present, such as during gravity release or dynamic control of active optics.
- No measurable hysteresis results from thermal cycling of Corning 7973.

Chemical Durability

- Excellent resistance to weathering.
- Exhibits virtually no surface clouding or electrical surface leakage when subject to attack by water, sulfur dioxide, and atmosphere gases.
- High Resistance to attack by nearly all chemical agents.

Solution @ 95 ˚C	Test Duration	Weight Loss
5% HCl	24 hrs	< 0.01 mg/cm^2
5% NaOH	6 hrs	0.9 mg/cm^2
0.02N Na_2CO_3	6 hrs	0.02 mg/cm^2
5% H_2SO_4	24 hrs	< 0.01 mg/cm^2
H_2O	24 hrs	< 0.01 mg/cm^2

Mechanical Properties

Unless otherwise stated, all values @ 25 °C

Elastic Modulus (E)	67.6 GPa
Shear Modulus	29.0 GPa
Bulk Modulus	34.1 GPa
Poisson’s Ratio	0.17
Density	2.21 g/cm^3
Knoop Hardness (200g load)	460 kg/mm^2
Ultimate Tensile Strength	49.8 MPa
Specific Stiffness (E/ρ)	3.12 x 10^6 m

TSG
Titania Silicate Low Expansion Glass

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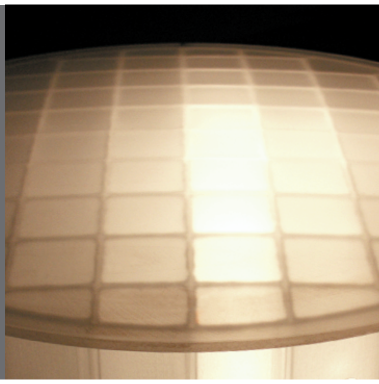


Advanced Optics and Materials

TSG, Titania Silicate Low Expansion Glass is the newest member of Corning's titania silicate low expansion glass family. TSG has a similar composition to ULE® and is made using the same flame hydrolysis process. TSG has a relaxed Absolute CTE requirement for those applications that do not require a zero CTE material, however CTE variation remains controlled through process discipline.

Linear Coefficient of Thermal Expansion — CTE

The guaranteed maximum limits for absolute CTE are as follows:

TSG The mean CTE shall be 0 ± 100 ppb/°C from 5°C to 35°C with a 95% confidence level.

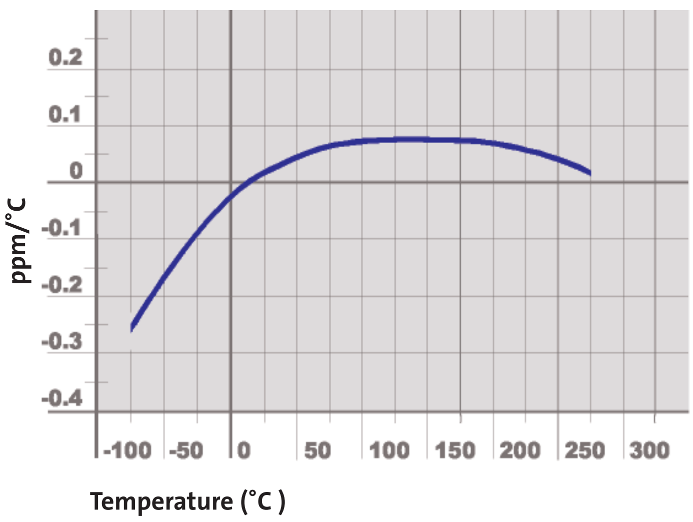
CTE Variation and Inclusion Quality Grades:

Inclusion Quality—The guaranteed maximum limits for seeds, bubbles and opaque inclusions are as follows:

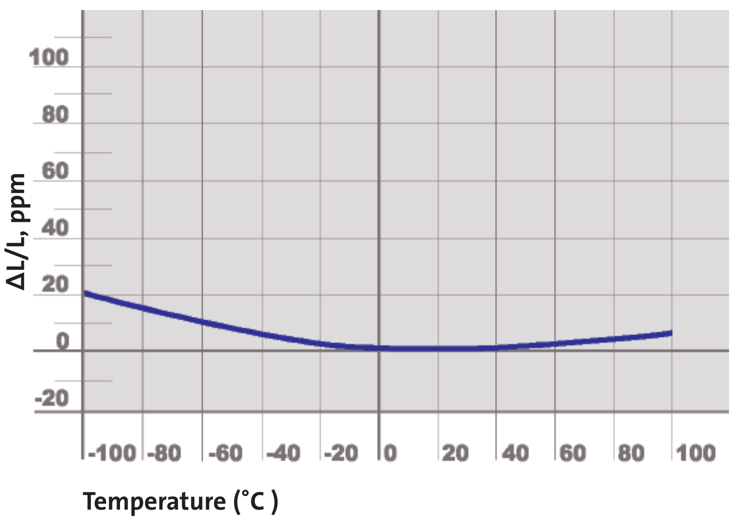
Quality Grade Selection Chart

	Maximum CTE Variation (ppb/°C)		Optical Retardation	Inclusions		
Grade	**Radial Range**	**Axial Range**	**Birefringence (nm/cm)**	**Inclusion Quality**	**Diameter < 20"**	**Diameter 20" to 56"**
Mirror Grade	30	20	35	**Critical Zone:**		
				Inclusion Max Mean Diameter	0.040"	0.080"
				Inclusions per cubic inch	4	6
				Avg. no. of inclusions per cubic inch	0.1	0.2
				Non-Critical Zone:		
				Inclusion Max Mean Diameter	0.100"	0.250"
				Inclusions per cubic inch	N/S	N/S
				Avg. no. of inclusions per cubic inch	0.2	0.6
Standard Grade	30	20	35	Inclusion Max Mean Diameter	0.100"	0.250"
				Inclusions per cubic inch	N/S	N/S
				Avg. no. of inclusions per cubic inch	0.2	0.6

Instantaneous CTE



Thermal expansion



Properties:
Unless otherwise stated, all values @ 25 ºC

Thermal Properties:

Mean coefficient of thermal expansion 5–35 ºC (∝)	0 ± 100 x 10^{-9}/K [0 ± 100 ppb/ºC]	Mean specific heat (C_p)	767 J/kg [0.183 cal/g]
Thermal conductivity (K)	1.31 w/(m • ºC) [1.31 kcal/(m • hr • ºC)	Strain point	890 ºC [1634 ºF]
Thermal diffusity (D)	0.0079 cm^2/s	Annealing point	1000 ºC [1832 ºF]
D.C. volume resistivity, 200 ºC, 100Hz (R)	$10^{11.6}$ ohm • cm	Softening point (estimated)	1490 ºC [2714 ºF]

Mechanical Properties:

Poisson's ratio (ν)	0.17	Specific stiffness (E/ρ)	3.12 x 10^6 m [1.23 x 10^8 in.]
Ultimate tensile stress (MOR)	49.8 MPa [7220 psi]	Shear Modulus (G)	29.0 GPa [4.20 x 10^6 psi]
Knoop Hardness, 200g load	460 kg/mm^2	Bulk Modulus (K)	34.1 GPa [4.95 x 10^6 psi]
Density (ρ)	2.21 g/cm^3 [0.079 lbs./in^3]	Elastic Modulus(E)	67.6 GPa [9.80 x 10^6 psi]

Chemical durability:

- Excellent resistance to weathering.
- Exhibits virtually no surface clouding or electrical surface leakage when subject to attack by water, sulfur dioxide, and atmospheric gases.
- High resistance to attack by nearly all chemical agents.

Solution @ 95ºC	Test duration	Weight loss
5% HCI	24 hrs.	<0.01 mg/cm^2
5% NaOH	6 hrs.	0.9 mg/cm^2
.02N Na_2CO_3	6 hrs.	0.02 mg/cm^2
5% H_2SO_4	24 hrs.	<0.01 mg/cm^2
H_2O	24 hrs.	<0.01 mg/cm^2

- CTE verification is achieved through a non destructive ultrasonic method.
- Stability— Excellent long term dimensional stability at room temperature. No residual figure change when taking a blank from 350ºC to water quench.
- Delayed elastic effect —There has been no measurable delayed elastic effect in TSG. This is an important consideration when large strain is present during fabrication or when environmental loading is present, such as during gravity release or dynamic control of active optics.
- No Measurable hysteresis results from thermal cycling regardless of the rate of temperature change.

Notes:

- Critical Zone — a quality layer typically extending to a depth of 0.200" below the surface specified by the customer for finishing.
- Non-Critical Zone — all glass outside the critical zone:
  - Inclusions with 0.005" or smaller mean diameter are disregarded.
  - Mirror and standard grades available in sizes up to 58" diameter or diagonal by 5" thick. Corning would be pleased to quote larger sizes to customer specs.
  - Tooling grade available. Please contact Corning for availability.

CORNING
Discovering Beyond Imagination

SPIE
Conference 2002

Characterization and Characteristics of a ULE®Glass Tailored for the EUVL Needs

By Dr. Phil Fenn, Dr. Ben Hanson, Dr. Ken Hrdina* and Dr. Rob Sabia

Abstract

Corning Incorporated is tailoring properties of ULE®Glass in order to meet the EUVL customer needs for mask substrates as well as optics. Improvements in ULE have been made in the areas of reduced inclusion levels [1], modeling predictions [2,3], reduced striae, and improved metrology capabilities [4]. Other properties inherent to ULE Glass that are conducive to optical applications include its thermal hysteresis [5,6], delayed elasticity [7,8], and temporal stability [9].

Inclusions

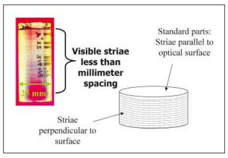
SEMI Draft 3148 currently require zero defects > 50 nm in size. Inclusions are not considered defects unless they manifest themselves on the surface of the substrate material. Predictions based on size and number of defects suggest only 1 defect expected in 300 substrates if the substrates were randomly selected. The observed inclusions were gaseous. The current technique is not capable of observing inclusions less than 1 µm in size.

Surface Defect Predictions…

Inclusion density	Predictions
0.002 inc/cm³	1 Defect in 300 Substrates

Striae

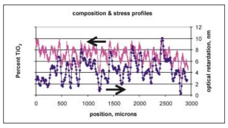
Striae present in ULE Glass is the result of small changes in the index of refraction that occurs as a result of small compositional difference in this binary glass. Standard parts have the optical surface parallel to the direction of the striae.



Developed Metrology

Microprobe

The microprobe technique has been refined to readily allow compositional variations to be measured that correlate to CTE variations of a few ppb/°C. This technique allows evaluation of CTE variations on a micron scale!

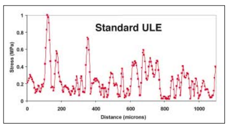


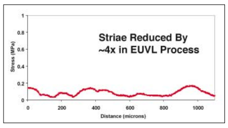
Polariscope

A polariscope was also used to evaluate striae within ULE Glass. Several metrology means are available for ready characterization of striae.

Striae Reduction

Process changes were made to reduce striae in ULE. The rms stress level between striae has been reduced by ~4x in this initial experiment. Development efforts are focusing on additional improvements.





Homogeneity

Measurement

The inherent properties of ULE enable the non-destructive assessment of CTE homogeneity over any part.

Mask Substrates

Glass is readily available today that meets SEMI Draft 3148 class A specifications for CTE homogeneity which is ±5ppb/K.

Optics

Although no homogeneity specification exists at the moment, improvements will likely be needed.

CTE Accuracy and Control

The current process is flexible and readily allows for targeting specific zero cross-over temperatures.

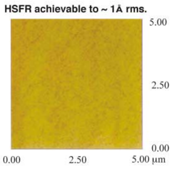
For Absolute CTE Measurements See:

4688-54: Vivek Badami and Michael Linder

Ability to Polish

Optics and photomask substrates require HSFR values to less than 0.15 nm rms. ULE Glass has been demonstrated to be polishable to levels below this specification by many [10,11,12].

HSFR achievable to ~ 1Å rms.



Development Roadmap

	2000	2001	2002	2003	2004
Inclusion #/cm³	0.02	0.002	0.002	0.002	0.001
Predictions*	1 in 25	1 in 300	1 in 300	1 in 300	1 in 600
Striae (p-v Mpa)	±1.00	±0.20	±0.10	±0.05	±0.04 TBD
CTE Metrology: Precision (100 mm)	±0.4 ppb/K	Evaluate	Specify Equipment	±0.2 ppb/K	±0.1 ppb/K
CTE Metrology: Absolute		Evaluate	Design and Build	Debug and correlate	Quality control

Development Program

The development program underway at Corning Incorporated is designed to:

- Further reduce striae
- Improve CTE accuracy to < 1ppb/K
- Improve CTE precision in 100 mm glass from ±0.4 ppb/K to ±0.1 ppb/K
- Improve glass 3-D homogeneity
- Reduce birefringence levels

References

(1) Hrdina, Brewer,and Kenney, "Inclusions Within ULE Glass", 2nd Annual EUVL Workshop, Oct 2000.
(2) Meda, "Reflecting-Surface Distortion When Mirrors are Cut to Shape", Proceedings ofSPIE 26th Annual Symposium ML,(Vol 4343) March 2001.
(3) Roux, Meda, Spence, "Applicability of ULE for EUVL", 2nd Annual EUVL Workshop, Oct, 2000.
(4) Hrdina, Hamilton, Kenney, "A Recent Look at CTE in ULE", 2nd Annual EUVL Workshop, Oct 2000.
(5) Shaffer and Bennett, "Effect of Thermal Cycling on Dimensional Stability of Zerodur and ULE," Applied Optics, 23 [17] 2852-2853, September 1, 1984.
(6) Jacobs, Johnston, Sasian,Watson, Targrove, and Bass, "Surface Figure Changes Due to Thermal Cycling Hysteresis," App. Opt., 26 [20] Oct. 15, 1987.
(7) Pepi and Golini, "Delayed Elastic Effects in the Glass Ceramic Zerodur and ULE at Room Temperature," Applied Opt., 30 [22], 3087-3088 Aug 1, 1991.
(8) Wilkins, Coon and Epstein, "Elastic Hysteresis Phenomena in ULE and Zerodur Optical Glasses at Elevated Temperatures," SPIE, 970, 40-46, (1988).
(9) Gulati and Edwards, "ULE-Zero Expansion, Low Density, and Dimensionally Stable Material for Lightweight Optical Systems, CR67 July 27-28, 1997.
(10) Aschke, "EUVL Development Activities at Schott Lithotec," EUVL Workshop, 10-2001.
(11) Blaedel,Taylor,Walton,Hector, and Ramamoorthy, EUVL Workshop, Oct, 2000.
(12) Hendron and Baker, "LTEM Substrate Development for EUV," NGL Workshop, 8/01.

Improved Characteristics of ULE® Glass for Meeting EUVL Needs

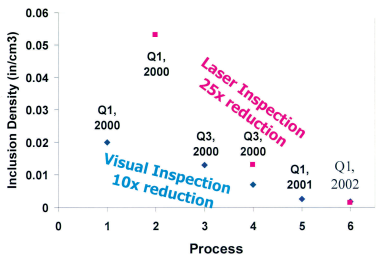
SPIE
Conference 2003

Brad Ackerman, Vivek Badami, Rich Fiacco, Chris Heckle, Dave Jenne,
Kenneth Hrdina, Mike Linder, John Maxon, Brent McLean, Dave Navan, Rob Sabia, and Mike Wasilewski

Introduction:

ULE® Glass is a low expansion silicate glass that has been historically used for ground and space based telescope mirrors. Industry experts have now identified ULE Glass as a material of choice for EUVL, with some property improvement required. Striae and homogeneity are two properties which require improvement for optics applications. Striae in standard ULE glass has been found to impact mid spatial frequency roughness of optics. EUVL grade ULE Glass has been tailored to eliminate this issue. Metrology tools are being developed to meet homogeneity needs.

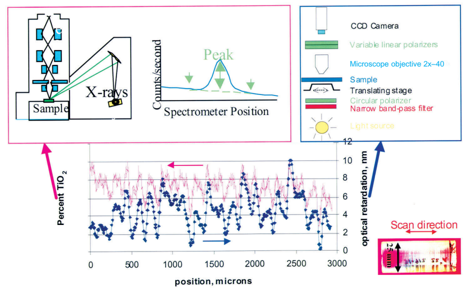
Inclusion Reduction ... Results from 1999–2002



Metrology Improvement:
Laser system increases detection limit from 80 µm to 1 µm.

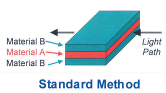
Material Improvement:
Shows inclusions reduced 10 to 25x.

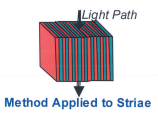
Further Characterizing of Striae



Striae characterized as compositional differences and also stress differences within glass.

Evaluatin Striae with: Sandwich Seal* Test





$$\Delta\alpha = [\Delta\lambda(1-\mu)/E\omega K][1+(t_c/2t_o)]10^9/\Delta T$$

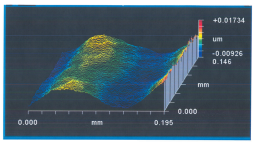
Where:
- $\Delta\alpha$ = Thermal expansion difference (ppb/K)
- $\Delta\lambda$ = optical retardation (nm)
- μ = Poisson ratio, (0.17)
- E = Young's modulus, (67.6GPa)
- ω = Width of seal (path length), cm
- K= Stress Optic Coefficient of glass, 0.290 nm/cm/psi (ULE Glass)
- t_c = Thickness of central seal member, cm
- t_o = Thickness of outer seal member, cm
- ΔT= Temperature difference from RT to setting point, 925-25°C = 900°C

Sandwich seal approximations used to estimate the CTE differences within striae layers based on Stresses between layers.

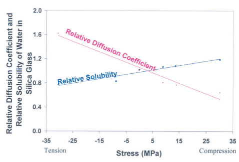
~Δ1 MPa stress ≈ Δ20.5 ppb/K CTE

*Hagy, Applied Optics, 12 [7] (1973).

CMP Polishing



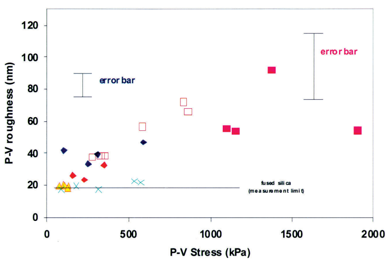
Smoothness of surface suggests primarily chemical removal during super-polishing (lack of fracture surfaces).



Nogami and Tomozawa, J. Am. Cer. Soc. 1984.

Stress state in silica glass known to impact diffusion and solubility of water into glass*.

Correlating Roughness to Stress within Striae

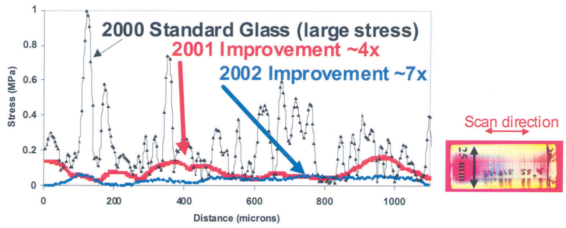


Conclusions:

Reduced stress within striae reduces roughness.

P-V roughness sensitive to polish procedures.

Striae Reduction ... Results from 2001–2002



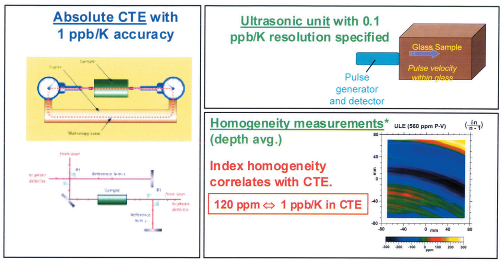
Metrology Implementation:

Microprobe and polarimeter identified as metrology tools.

Material Improvement:

Shows striae stress levels reduced 7x

Metrology Improvements Needed ... 2002–2004



**Data and graph courtesy of M. Johnson, and G. Sommargen.*

Metrology:

Identified new equipment required to meet EUVL specifications.

Construction and purchase of equipment precedes material improvements.

Material:

CTE low frequency homogeneity improvements required.

Property and Characterization Roadmap

	2000	2001	2002	2003	2004	2005
CTE crossover *Mask Class A (ppb/K)*	±5	±5	±5	±5	±4 *TBD*	±3 *TBD*
CTE TSR *Mask Class A (ppb/K)*	10	6	6	5	4	3
Inclusions *(> 1micron) #/cm3*	0.02	0.002	0.002	0.002	0.001	0
Inclusions *Mask Failure Predictions*	1 in 25	1 in 300	1 in 300	1 in 300	1 in 600	None
Striae *(p-v Mpa)*	±1.00	±0.20	±0.10	±0.05	±0.04 *TBD*	±0.04 *TBD*
CTE Homogeneity Optics *radial p-v (ppb/K)*	10 ULE Premium Grade	10 ULE Premium Grade	8 ULE EUV Grade	5 ULE EUV Grade	5 ULE EUV Grade	5 ULE EUV Grade
CTE Homogeneity Optics *axial p-v (ppb/K)*	16 ULE Premium Grade	14 ULE Premium Grade	10 ULE EUV Grade	9 ULE EUV Grade	8 ULE EUV Grade	6 *TBD* ULE EUV Grade
CTE Crossover Optics *(ppb/K)*	---	±5	±5	±4	±3	±2 *TBD*
Birefringence *(nm/cm)*	10 ULE Premium Grade	10 ULE Premium Grade	4 ULE EUV Grade	<3 ULE EUV Grade	<2 ULE EUV Grade	<1 ULE EUV Grade
Index Homogeneity *masks (ppm)*	---	---	600 ULE EUV Grade	TBD	TBD	TBD
CTE Metrology *ultrasonic Precision (100mm)*	±0.4 ppb/K	Evaluate	Specify Equipment	±0.2 ppb/K	±0.1 ppb/K	±0.1 ppb/K
CTE Metrology *Index Homogeneity*	---	---	Evaluate	±0.1 ppb/K	±0.1 ppb/K	±0.05 ppb/K
CTE Metrology *Microprobe Precision*	±2 ppb/K	±2 ppb/K	±2 ppb/K	±2 ppb/K	±2 ppb/K	±2 ppb/K
CTE Metrology *XRF Precision*	±2 ppb/K	±2 ppb/K	±2 ppb/K	±2 ppb/K	±2 ppb/K	±2 ppb/K
CTE Metrology *Absolute*	---	Evaluate	Design and Build	Debug and Correlate	Quality control	Operational studies

Summary and Conclusions:

EUVL grade ULE Glass is an appropriate material for EUV applications. A roadmap for glass quality and metrology improvements is being pursued. Striae effect on surface roughness has been investigated and the impact reduced. This was accomplished by characterizing the striae, developing the proper metrology tools and improving the forming process. Future work will focus on improving the low frequency CTE homogeneity within ULE and the development of appropriate metrology tools.

HPFS® 7979, 7980 and 8655 Fused Silica

Dedication to technology leadership and world-class metrology capabilities play a major role in Corning's ability to produce leading edge materials. Corning is committed to ensuring that its customers are provided qualified, authentic products.

Corning has a minimum of 25 years of measurement experience and provides a certificate of compliance for each sale of product to verify the authenticity of our HPFS® Fused Silica Materials.

Fused Silica is offered in many different grades to support various product applications. Glass codes 7980, 7979, and 8655 are high purity non-crystalline silica glasses with excellent optical qualities.

Product characteristics include extraordinary low refractive index variations leading to state-of-the-art homogeneity values, lowest birefringence values, large size capabilities, exceptional transmittance from the deep ultraviolet through the infrared region, and an ultra-low thermal expansion coefficient; all of which are critical to our customers' demanding needs.

HPFS® Summary of Key Attributes

	Fused Silica						
Attribute	7980 Standard Grade	7980 KrF Grade	7980 ArF Grade	7980 Mirror Grade	7980 Industrial Grade	7979 IR Grade	8655 ArF Grade
Visible Transmittance	■	■	■	■	■	■	■
UV Transmittance	■	■	■				■
Infrared Transmittance						■	■
Homogeneity Certified in Use-Axis AA, A, C, F (By Size)	■	■	■			■	■
Inclusion Class Certified 0, 1, 2, 5	■	■	■	■		■	■
Striae Certified ISO 10110-4 Class 5 (None)	■	■	■	■		■	■
Homogeneity Certified in Off-Axis AA, A, C, F (By Size)	■	■	■			■	■
Low Birefringence	■	■	■	■		■	■
UV Laser Resistant (Data available upon request)		■	■				■
Economical (No certification of any properties except visible transmission. Tooling applications.)					■		

Quality Grade Selection Chart

For Mirror Grade - see chart on next page

Inclusion Class			Homogeneity[3,4] [ppm]							
			Grade							
Class	Total Inclusion Cross Section[1] [mm²]	Maximum Size[2] [mm]	AA ≤ 0.5	A ≤ 1	B ≤ 1.5	C ≤ 2	D ≤ 3	E ≤ 4	F ≤ 5	G NS[5]
0	≤0.03	0.10	■	■	■	■	■	■	■	■
1	≤0.10	0.28		■	■	■	■	■	■	■
2	≤0.25	0.50			■	■	■	■	■	■
3	≤0.50	0.76				■	■	■	■	■
4	≤1.00	1.00				■	■	■	■	■
5	≤2.00	1.27				■	■	■	■	■

1. Defines the sum of the cross section in mm^2 of inclusions per 100 cm^3 of glass. Inclusions with a diameter ≤ 0.10 mm are disregarded.
2. Refers to the diameter of the largest single inclusion.
3. Index homogeneity: the maximum index variation (relative), measured over the clear aperture of the blank.
4. Index homogeneity is certified using an interferometer at 632.8 nm. The numerical homogeneity is reported as the average through the piece thickness. Blanks with a diameter up to 450 mm can be analyzed over the full aperture. Larger parts can be analyzed using multiple overlapping apertures. The minimum thickness for index homogeneity verification is 20 mm. For thinner parts, the parent piece is certified.
5. NS (Not Specified)

HPFS® Data and Properties

	Inclusion Class	Homogeneity Grade	Birefringence Lower specifications available upon request [nm/cm]	Striae ISO 10110-4 Class	Metallic Impurities [ppb]	OH Content [ppm]
7979 IR Grade	0, 1, 2	AA, A, C, F	≤ 5	5	< 100	< 1
7980 Standard Grade**	0 - 5	AA - F	≤ 5	5	< 1000	800 - 1000
7980 KrF Grade*	0, 1, 2	AA, A, C, F	≤ 1	5	< 500	800 - 1000
7980 ArF Grade*	0, 1, 2	AA, A, C, F	≤ 1	5	< 100	800 - 1000
7980 Mirror Grade	See below	NS	≤ 5	1	NS	800 - 1000
7980 Industrial Grade	NS	NS	≤ 5	1	NS	800 - 1000
8655 ArF Grade*	0, 1, 2	AA, A, C, F	≤ 1	5	< 10	< 1

* No visible fluorescence when exposed to deuterium source from 215 nm - 400 nm. Material contains hydrogen to minimize absorption under UV exposures.
** HPFS® 7980 Standard Fluorescence-Free Grade available upon request.

Mechanical Properties

Unless otherwise stated, all values @ 25 °C	
Elastic (Young's) Modulus	73 GPa
Shear Modulus	31 GPa
Modulus of Rupture, abraded	52.4 MPa
Bulk Modulus	35.9 GPa
Poisson's Ratio	0.16
Density	2.20 g/cm³
Knoop Hardness (100g load)	522 kg/mm²
Tensile Strength	54 MPa
Compressive Strength	1.14 GPa

Thermal Properties

Glass Code:	7980	7979	8655	Viscosity
Softening Point*	1585 °C	1627 °C	1627 °C	$10^{7.6}$ poises
Annealing Point*	1042 °C	1180 °C	1180 °C	10^{13} poises
Strain Point*	893 °C	1068 °C	1068 °C	$10^{14.5}$ poises
Specific Heat			0.770 J/(g K)	
Thermal Conductivity			1.38 W/(m K)	
Thermal Diffusivity			0.0075 cm²/s	
Thermal Expansion** (ppm/C):				
5 °C to 35 °C			0.52×10^{-6}	
0 °C to 200 °C			0.57×10^{-6}	
-100 °C to +200 °C			0.48×10^{-6}	
ASTM Procedures - *C-598, **E-228				

Mirror Quality Grade Selection Chart

Mirror Grade: Inclusion Classes			
Critical Zone:	Blank Dimensions (Diameter or Diagonal)		
	< 508 mm (20")	508 - 1143 mm (20 - 45")	1143 - 2286 mm (45 - 90")
Max. Mean Diameter	0.254 mm (0.010")	0.762 mm (0.030")	1.524 mm (0.060")
Max. Avg. #/mm³ (#/in³)	2 ppm (0.04)	3 ppm (0.05)	5 ppm (0.08)
Non-Critical Zone:	Blank Dimensions (Diameter or Diagonal)		
	< 508 mm (20")	508 - 1143 mm (20 - 45")	1143 - 2286 mm (45 - 90")
Max. Mean Diameter	1.016 mm (0.040")	1.524 mm (0.060")	3.81 mm (0.150")
Max. Avg. #/mm³ (#/in³)	3 ppm (0.05)	3 ppm (0.05)	9 ppm (0.15)

Refractive Index and Dispersion: HPFS® 7980

Conditions: 22 °C, 760 mm Hg, N_2

Wavelength [Vacuum] [nm]	Refractive Index[2] n	Thermal Coefficient $\Delta n/\Delta T$[3] [ppm/C]	Polynomial Dispersion Equation Constants[1], 22 °C	
1128.950	1.448866	9.6	A_0	2.104025406E+00
1014.260 n_t	1.450241	9.6	A_1	-1.456000330E-04
852.344 n_s	1.452463	9.7	A_2	-9.049135390E-03
706.714 n_r	1.455144	9.9	A_3	8.801830992E-03
656.454 n_C	1.456364	9.9	A_4	8.435237228E-05
632.990	1.457016	10.0	A_5	1.681656789E-06
587.725 n_d	1.458461	10.1	A_6	-1.675425449E-08
546.227 n_e	1.460076	10.2	A_7	8.326602461E-10
486.269 n_F	1.463123	10.4		
435.957 n_g	1.466691	10.6	Sellmeier Dispersion Equation Constants[2], 22 °C	
404.770 n_h	1.469615	10.8	A_1	0.68374049400
365.119 n_i	1.474539	11.2	A_2	0.42032361300
334.244	1.479764	11.6	A_3	0.58502748000
312.657	1.484493	12.0		
253.728	1.505522	13.9	B_1	0.00460352869
228.872	1.521154	15.5	B_2	0.01339688560
214.506	1.533722	17.0	B_3	64.49327320000
206.266	1.542665	18.1		
194.227	1.558918	20.3	$\Delta n/\Delta T$ Dispersion Equation Constants[3], 20-25 °C	
184.950	1.575017	22.7	C_0	9.390590
			C_1	0.235290
			C_2	-1.318560E-03
			C_3	3.028870E-04
			Other Optical Properties	
			nF'-nC'	0.006797
			Stress Coefficient	35.0 nm/cm MPa
			Abbe Constants:	
			V_e	67.6
			V_d	67.8

*1 Polynomial Equation: $n^2 = A_0 + A_1 \lambda^4 + A_2 \lambda^2 + A_3 \lambda^{-2} + A_4 \lambda^{-4} + A_5 \lambda^{-6} + A_6 \lambda^{-8} + A_7 \lambda^{-10}$ with λ in µm

*2 Sellmeier Equation: $n^2 - 1 = A_1\lambda^2/(\lambda^2 - B_1) + A_2 \lambda^2/(\lambda^2 - B_2) + A_3 \lambda^2/(\lambda^2 - B_3)$ with λ in µm

*3 $\Delta n/\Delta T$ Equation: $\Delta n/\Delta T$ [ppm/C] $= C_0 + C_1\lambda^{-2} + C_2\lambda^{-4} + C_3\lambda^{-6}$ with λ in µm

The above dispersion equations were fit to the refractive indices of 20 wavelengths from 1129 nm to 185 nm.

Refractive Index and Dispersion: HPFS® 8655 and 7979

Conditions: 22 °C, 760 mm Hg, N_2

Wavelength [Vacuum] [nm]	Refractive Index[1] n	Thermal Coefficient[2] Δn/ΔT [ppm/C]	Sellmeier Dispersion Equation Constants[1], 20 °C	
2326.050	1.433027	8.7	A_1	7.033574317E-02
2058.650	1.437307	9.3	A_2	7.241205497E-01
1970.630	1.438601	9.6	A_3	3.097807778E-01
1813.570	1.440776	9.1	A_4	9.309957497E-01
1530.000	1.444337	9.7	B_1	-2.301552288E-03
1128.950	1.448930	9.7	B_2	6.272886117E-03
1014.26 n_t	1.450304	9.6	B_3	1.415449740E-02
852.344 n_s	1.452526	9.5	B_4	1.016434845E+02
780.237	1.453731	9.5		
706.714 n_r	1.455205	9.9	Sellmeier Dispersion Equation Constants[1], 22 °C	
656.454 n_C	1.456425	10.1	A_1	3.550277875E-02
644.025 $n_{C'}$	1.456763	10.1	A_2	7.353314507E-01
632.990	1.457077	9.9	A_3	3.334560303E-01
587.725 n_d	1.458522	10.2	A_4	9.269506614E-01
546.227 n_e	1.460135	10.5	B_1	-4.826183477E-03
486.269 n_F	1.463183	10.4	B_2	5.808687673E-03
480.126 $n_{F'}$	1.463561	10.4	B_3	1.399572492E-02
435.957 n_g	1.466751	10.7	B_4	1.012182926E+02
404.770 n_h	1.469674	10.9		
388.975	1.471446	10.9	Sellmeier Dispersion Equation Constants[1], 25 °C	
365.119 n_i	1.474599	11.3	A_1	2.623483282E-02
340.463	1.478646	11.6	A_2	7.306029048E-01
334.244	1.479824	11.7	A_3	3.475321572E-01
312.657	1.484554	12.0	A_4	9.216052441E-01
296.814	1.488798	12.5	B_1	-5.783959035E-03
289.444	1.491056	12.5	B_2	5.600103210E-03
253.728	1.505585	14.0	B_3	1.389808930E-02
228.872	1.521218	15.3	B_4	1.006578079E+02
226.572	1.523018	15.9		
214.506	1.533786	16.8	Δn/ΔT Dispersion Equation Constants[2], 20-25 °C	
213.923	1.534371	17.0	D_0	9.545124E+00
206.266	1.542731	18.2	D_1	-9.835579E-02
202.613	1.547213	18.3	D_2	2.003170E-01
194.227	1.558985	20.4	D_3	2.209816E-03
184.950	1.575091	22.1	D_4	1.980644E-04

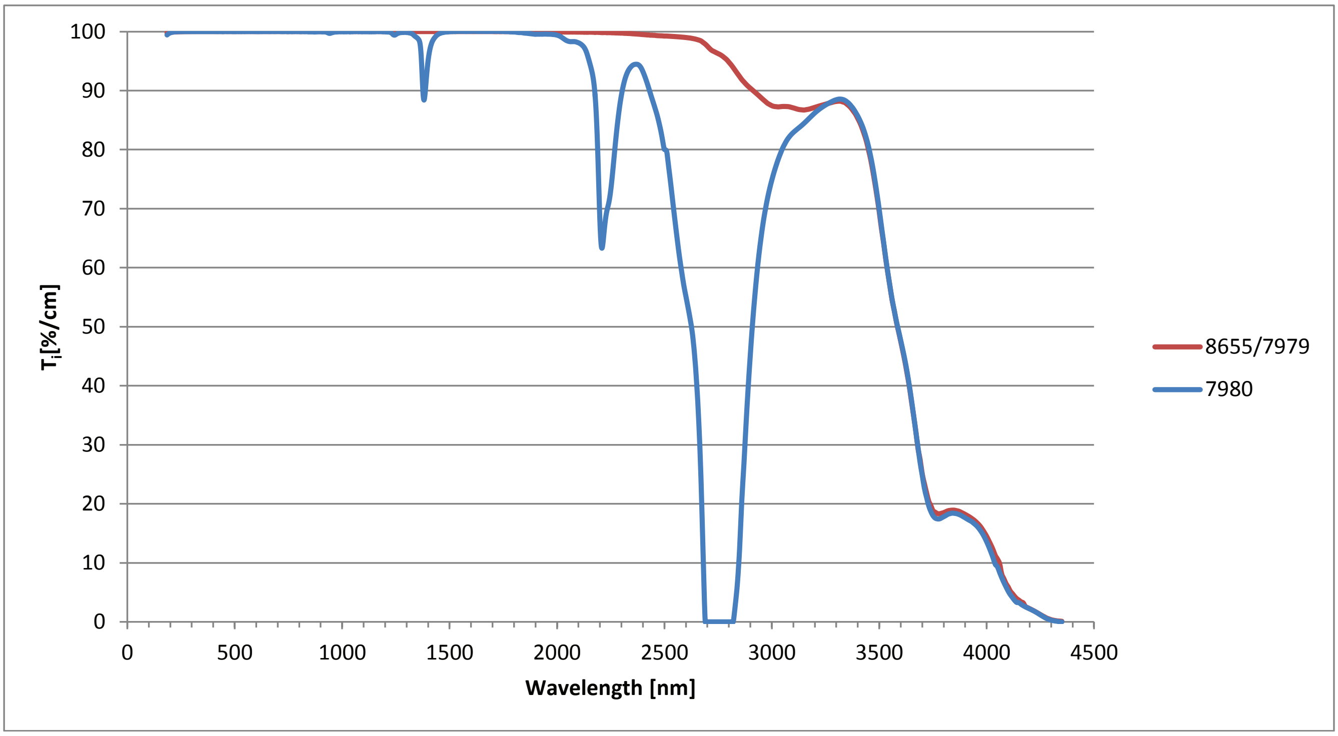
Other Optical Properties	
nF'-nC'	0.006797
Stress Coefficient	35.0 nm/cm MPa
Abbe Constants:	
V_e	67.6
V_d	67.8

**1 Sellmeier Equation: $n^2-1 = A_1 \lambda^2/(\lambda^2 - B_1) + A_2 \lambda^2/(\lambda^2 - B_2) + A_3 \lambda^2/(\lambda^2 - B_3) + A_4 \lambda^2/(\lambda^2 - B_4)$ with λ in µm*

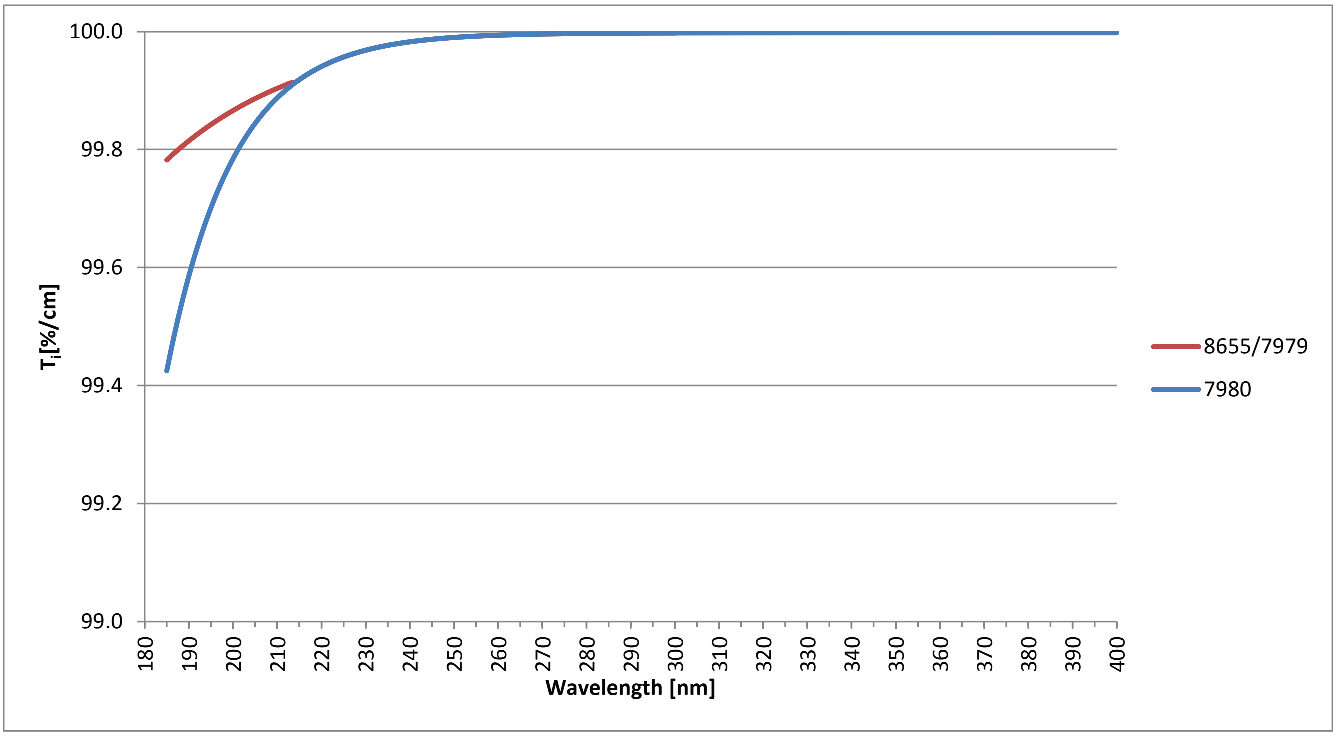
**2 Δn/ΔT Equation: $\Delta n/\Delta T\ [ppm/C] = D_0 + D_1\lambda^2 + D_2\lambda^{-2} + D_3\lambda^{-4} + D_4\lambda^{-6}$ with λ in µm*

The above Sellmeier dispersion equation was used to fit the refractive indices of 35 wavelengths from 2326 nm to 185 nm.

Broad Spectrum Internal Transmittance



UV Internal Transmittance



HPFS® 7980 Standard Grade meets high $T_i \geq 88.00$ %/cm @185 nm. (Equivalent to $T_e \geq 80.00$ %/cm @185 nm)
HPFS® 7980 KrF Grade meets high $T_i \geq 99.90$ %/cm @248 nm.
HPFS® 7980 ArF Grade meets high $T_i \geq 99.50$ %/cm @193 nm.
HPFS® 8655 Grade meets high $T_i \geq 99.75$ %/mm @193 nm.
HPFS® 8655 Grade Typical initial absorption k: ≤ 0.0001/cm at 193 nm.
Higher transmittance is available upon request.

Quality Grade Selection Chart

Inclusion Class			Homogeneity[3,4] [ppm]							
			Grade							
Class	Total Inclusion Cross Section[1] [mm]	Maximum Size[2] [mm]	AA ≤ 0.5	A ≤ 1	B ≤ 1.5	C ≤ 2	D ≤ 3	E ≤ 4	F ≤ 5	G NS[5]
0	≤0.03	0.10	■	■	■	■	■	■	■	■
1	≤0.10	0.28		■	■	■	■	■	■	■
2	≤0.25	0.50			■	■	■	■	■	■
3	≤0.50	0.76				■	■	■	■	■
4	≤1.00	1.00				■	■	■	■	■
5	≤2.00	1.27				■	■	■	■	■

1. Defines the sum of the cross section in mm^2 of inclusions per 100 cm^3 of glass. Inclusions with a diameter ≤ 0.10 mm are disregarded.

2. Refers to the diameter of the largest single inclusion.

3. Index homogeneity: the maximum index variation (relative), measured over the clear aperture of the blank.

4. Index homogeneity is certified using an interferometer at 632.8 nm. The numerical homogeneity is reported as the average through the piece thickness. Blanks with a diameter up to 450 mm can be analyzed over the full aperture. Larger parts can be analyzed using multiple overlapping apertures. The minimum thickness for index homogeneity verification is 20 mm. For thinner parts, the parent piece is certified.

5. NS (Not Specified)

HPFS® Data and Properties

	ISO 10110-1 Inclusion Class	Homogeneity Grade [ppm]	Birefringence Lower specifications available upon request [nm/cm]	ISO 10110-4 Striae Class	Metallic Impurities [ppb]
7979 IR Grade	0, 1, 2	AA, A, C, F	≤ 5	5	< 100
7979 Industrial Grade	NS	NS	≤ 5	NS	NS
7980 Standard Grade**	0 - 5	AA - F	≤ 5	5	< 1000
7980 KrF Grade*	0, 1, 2	AA, A, C, F	≤ 1	5	< 500
7980 ArF Grade*	0, 1, 2	AA, A, C, F	≤ 1	5	< 100
7980 Mirror Grade	See catalog	NS	≤ 5	NS	NS
7980 Industrial Grade	NS	NS	≤ 5	NS	NS
8652 ArF Grade*	0, 1, 2	AA, A, C, F	≤ 1	5	< 10
8655 ArF Grade*	0, 1, 2	AA, A, C, F	≤ 1	5	< 10

** No visible fluorescence when exposed to deuterium source from 215 nm - 400 nm. Material contains hydrogen to minimize absorption under UV exposures.*

*** HPFS 7980 Standard Fluorescence-Free Grade available upon request.*

HPFS® Summary of Key Attributes

Attribute	Fused Silica								
	7979 IR Grade	7979 Industrial Grade	7980 Standard Grade	7980 KrF Grade	7980 ArF Grade	7980 Mirror Grade	7980 Industrial Grade	8652 ArF Grade	8655 ArF Grade
Visible Transmittance	■	■	■	■	■		■	■	■
UV Transmittance			■	■	■			■	■
Infrared Transmittance	■							■	■
Homogeneity Certified in Use-Axis: AA, A, C, F (By Size)	■		■	■	■			■	■
Inclusion Class: 0, 1, 2, 5	■		■	■	■	■		■	■
Striae: ISO 10110-4 Class 5 (None)	■		■	■	■	■		■	■
Homogeneity Certified in Off-Axis: AA, A, C, F (By Size)	■		■	■	■			■	■
Low Birefringence	■		■	■	■	■		■	■
UV Laser Resistance (data available upon request)				■	■			■	■
Economical (No certification of any properties except visible transmission and birefringence. Tooling applications.)		■					■		

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