Viscoelastic deformation of glass substrates by laser patterned stressed films

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Abstract

Thin films are often used to change the reflection or transmission behavior of surfaces and optical components. However, they can also have an influence on the underlying substrate and deform it, for example by viscoelastic flow through thermal treatment. In order to utilize this effect for active forming, the process should be better understood.
For this purpose, the deformation of the optical glass substrate Schott-BK7 with a thin silicon suboxide layer is investigated. The deformation results mainly from the thermal stress on the thin film generated by annealing after deposition.
By irradiating the sample with a XeCl laser before heat treatment, part of the thin silicon suboxide layer is ablated in order to specifically modify the deformation of the substrate during annealing.

Materials

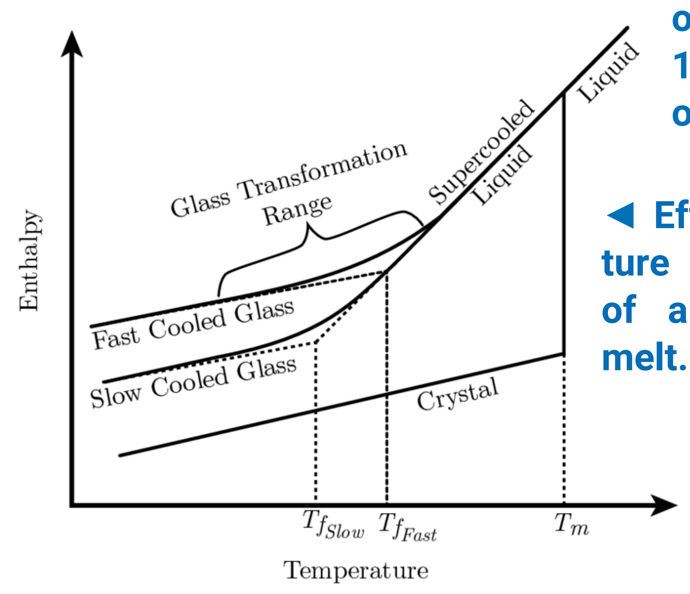
Schott BK7

- commercial, often used optical glass
- strain point ($\eta = 10^{13.5}$ Pa s): 524°C
- annealing point ($\eta = 10^{12}$ Pa s): 557°C

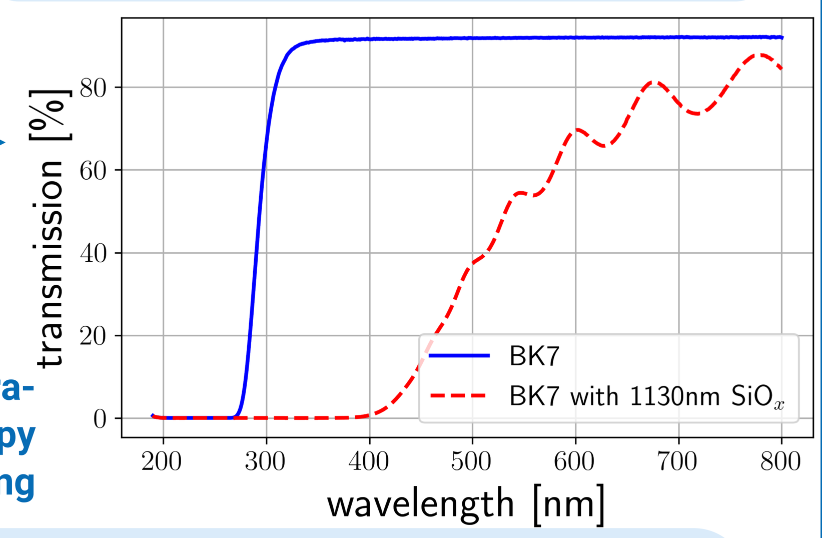
Silicon suboxide (SiO_x)

- strong UV-absorption
- heating leads to oxidation to SiO_2

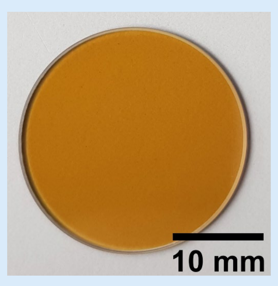
$$\eta = \eta_0 \cdot \exp^{\Delta H_\eta / RT}$$



◄ Effect of temperature on the enthalpy of a glass forming melt. [1]



Transmission ► of BK7 and 1130nm SiO_x on BK7.

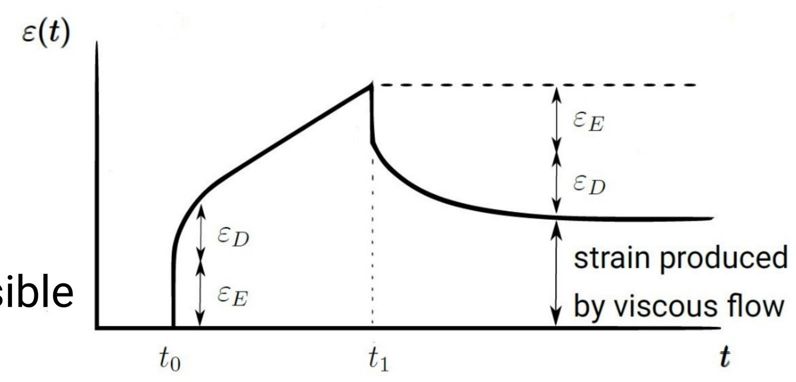


◄ 1130nm SiO_x coated on BK7.

Theory

Viscoelasticity

instantaneous elastic deformation ε_E
+
delayed elastic deformation ε_D — reversible
+
viscous flow — irreversible



▲ Schematic representation of the strain ε(t) when a constant stress σ_0 is applied to a viscoelastic material between t_0 and t_1. [2]

Stoney-Equation: [3]

- elastic curvature phenomena for closed coated substrates with layer thickness h_f << h_s substrate thickness

$$\kappa = \frac{6(1-\nu_s)}{E_s}\frac{h_f}{h_s^2}\sigma$$

viscoelastic analogy

$$\kappa_{ve}(t) = \frac{6h_f}{E_s h_s^2}\sigma\left(1-\nu_s+\frac{1+\nu_s}{3}\frac{t}{\tau_s}\right)$$

Wikström-Equation: [4]

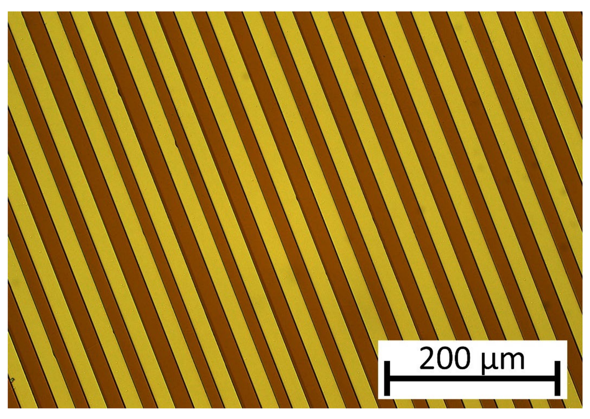
- describes elastic curvature phenomena for line patterned coated substrates

$$\kappa_p = -\frac{6h_f\sigma}{h_s^2 E_s}\frac{b}{d}\left(1-\chi(\rho)\,\nu_f-[1-\chi(\rho)]\,\nu_s\right)$$

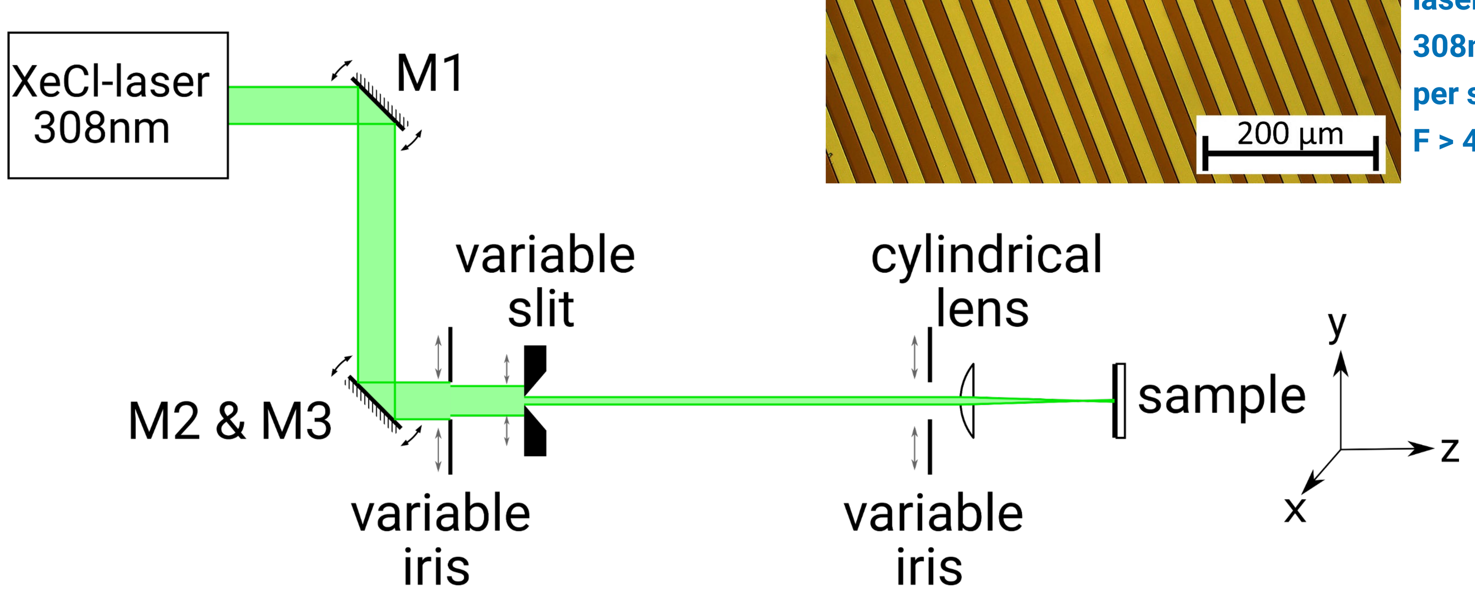
$$\kappa_s = -\frac{6h_f\sigma}{h_s^2 E_s}\frac{b}{d}\left(1-\chi(\rho)-[1-\chi(\rho)\,\nu_f]\,\nu_s\right)$$

Methods

Structuring of the samples [5]



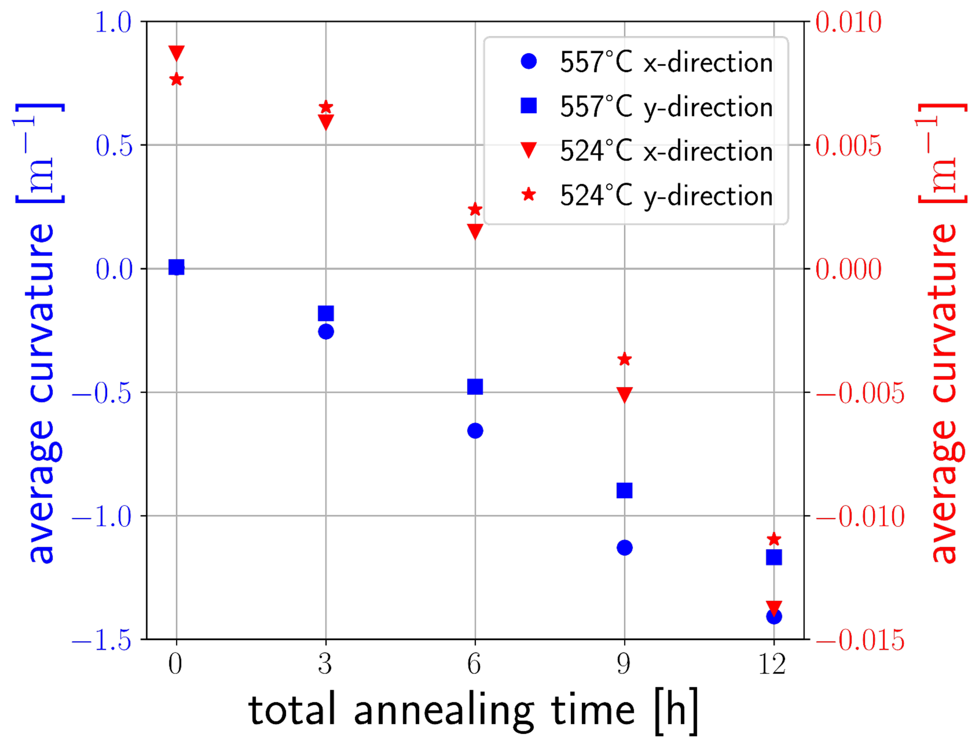
◄ Ablated line pattern. (line width: ~20µm; over whole sample) laser parameters: 308nm, 1Hz, 2 pulses per stripe, F > 450mJ/cm²



▲ Optical setup for rear side ablation (beam first passes through substrate and then through thin film) of lines from SiO_x on BK7.

Results

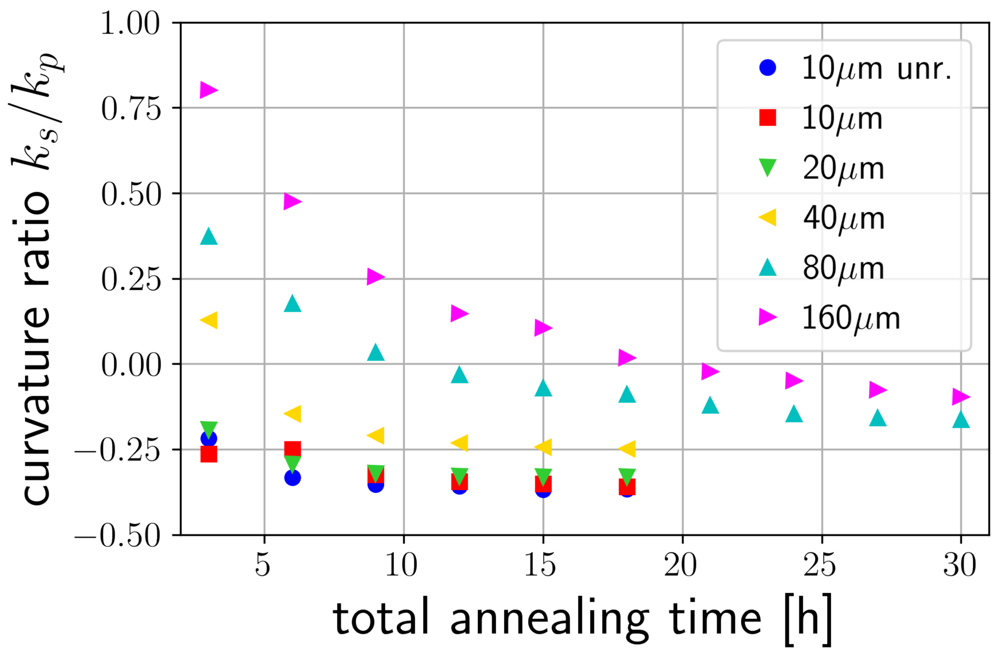
Temperature dependence



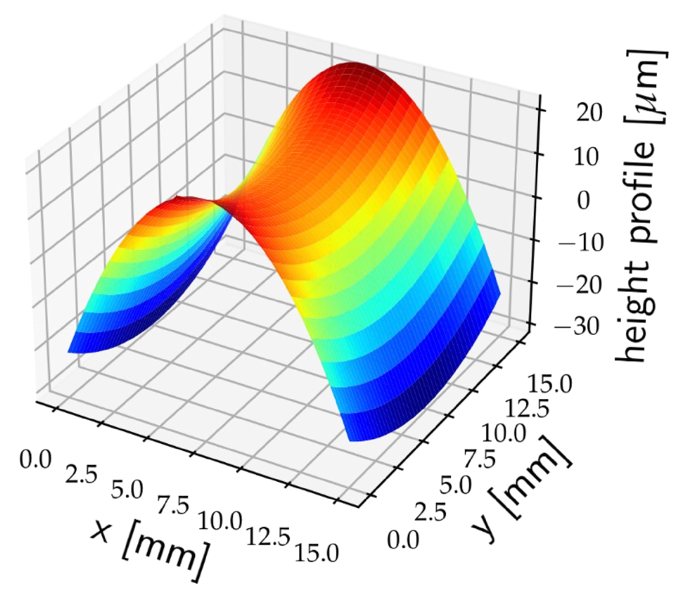
▲ Mean curvature versus total annealing time of samples heated at 524°C (red) and 557°C (blue) under oxygen atmosphere. The measurement error is estimated at $6 \cdot 10^{-3}$ m^{-1}.

- **isotropic deformation** due to **tensile stress**
- curvature evolution is highly affected by the annealing temperature
  ➡ **~30K** or **$10^{1.5}$Pa s** causes a difference of **two orders** of magnitude
- at these temperatures **no oxidation** of SiO_x to SiO_2 is observed

Samples with line pattern



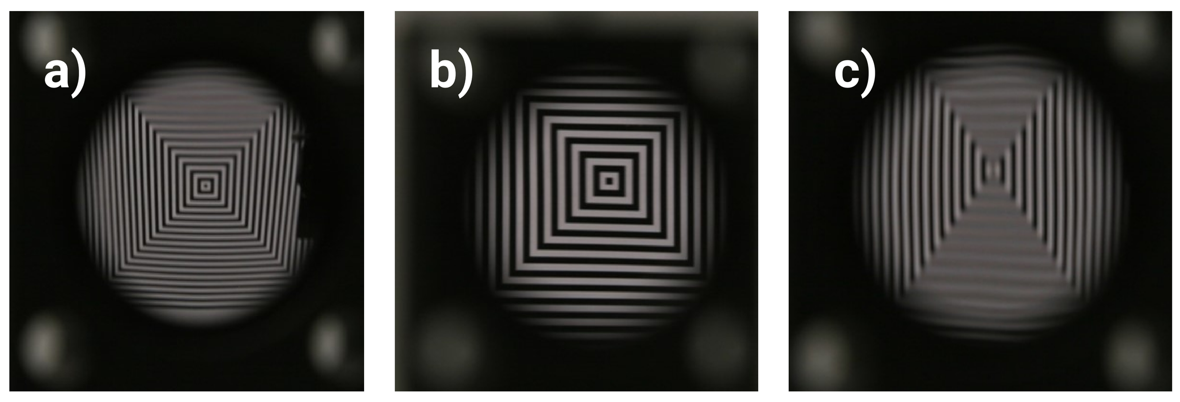
▲Curvature ratio against total annealing time of samples with different line width heated at 557°C under N_2-atmosphere.



▲ Surface topography (40µm line width) after 18h of annealing at 557°C in a N_2-atmosphere. (structured lines along the x-axis; visible lines along y-axis result from the measurement method)

- **precise ablation** of the SiO_x layer **possible**
- **perpendicular** to the lines:
  - small line widths: k>0 (uncoated side) ➡ concave deformation
  - large line widths (80µm,160µm): initially convex deformation (k<0), which then changes to concave deformation (k>0)
- **parallel** to the lines:
  convex deformation due to tensile stress, analogous to the closed layer
- **curvature ratio decreases asymptotically with time**:
  greater line width ➡ lower curvature ratio

Demonstrators



◄ Reflection of a pattern of concentric squares on aluminum-coated surfaces of: a) flat, b) convex (closed layer), c) concave-convex (line-structured) sample. The deformations in b), c) were caused by viscous flow due to heat treatment.

Conclusions and Outlook

The viscoelastic deformation of Schott-BK7 substrates with a SiO_x coating has an enormous sensitivity to temperature.
With closed layers, annealing resulted in an isotropic deformation of the sample, which further increased with time.
It is possible to structure the samples with a XeCl laser using rear side ablation. Thus, anisotropic deformations can be induced, e.g. by structuring with lines.
Our results contribute to the understanding of the viscous deformation of substrates and can also be used for the development of processes for the production of optics, especially individualized free-form optics.
But for this, further knowledge is needed about the influence of gravity during annealing and about the influence of the structure on deformation.

References

[1] Shelby, James E. *Introduction to glass science and technology*. Royal Society of Chemistry, 2005.
[2] Scherer, George W. "Relaxation in glass and composites." (1986).
[3] Stoney, George Gerald. "The tension of metallic films deposited by electrolysis." *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* 82.553 (1909): 172-175.
[4] Wikström, Adam, Peter Gudmundson, and Subra Suresh. "Thermoelastic analysis of periodic thin lines deposited on a substrate." *Journal of the Mechanics and Physics of Solids* 47.5 (1999): 1113-1130.
[5] Ihlemann, J., J. Meinertz, and G. Danev. "Excimer laser ablation of thick SiOx-films: etch rate measurements and simulation of the ablation threshold." *Applied Physics Letters* 101.9 (2012): 091901.