Anhang A

Berechnungen und Datenblätter

A.1 Verwendete Formelzeichen

a	Avalanche-Koeffizient
α_k	Absorptionskoeffizient für einen k-Photonen-Prozeß
β	Ionisationsrate
c	Lichtgeschwindigkeit
c_p	spezifische Wärmekapazität
d_0	mittlerer Defektabstand
E_p	Pulsenergie
E_{gap}...	Bandlücke („band gap“)
E_{ph} ...	Photonenenergie
F	Fluenz
F_0	Maximalfluenz in Gauß'förmiger Verteilung
F_{th}	Schwellfluenz
h	Ablationstiefe
Δh_p...	Ablationsrate (Tiefe pro Laserpuls)
H	Ablationsparameter (mittlere Eindringtiefe)
I	Intensität
k	Ordnung eines Mehrphotonenprozesses
K	thermische Diffusivität
λ	Wellenlänge
N	Pulszahl
n	Dichte der Leitungsband-Elektronen
ρ	Massendichte
t	Zeit
τ_G	Pulsdauer in zeitlich Gauß'förmiger Intensitätsverteilung (FWHM)
T	Temperatur
w_0	Gaußscher Strahlradius bei e^{-2}
ξ, Ξ...	Inkubationsparameter
z_d	Probendicke

A.2 Einige Umrechnungen

A.2.1 Kenngrößen der Gauß-Funktion

Eine Gauß'förmig verteilte Größe $Y(x)$ wird durch zwei Parameter bestimmt: den Maximalwert Y_0 und die charakteristische Strahlgröße. Für die Letztere wird i.A. eine der drei folgenden verwendet:

1. Halbwertsbreite (FWHM[1]) w_{FWHM} mit $Y(x = \frac{w_{FWHM}}{2}) = \frac{1}{2}Y_0$
2. 1/e-Radius w_e mit $Y(x = w_e) = Y_0 \cdot e^{-1}$
3. 1/e^2-Radius w_0 mit $Y(x = w_0) = Y_0 \cdot e^{-2}$

Entsprechend gilt

$$Y(x) = Y_0 \cdot e^{-4\ln(2)\frac{r^2}{w_{FWHM}^2}} = Y_0 \cdot e^{-\frac{r^2}{w_e^2}} = Y_0 \cdot e^{-2\frac{r^2}{w_0^2}}. \tag{A.1}$$

Die Umrechnung der charakteristischen Strahlgrößen ineinander kann erfolgen nach:

$$w_{FWHM} = 2\sqrt{\ln(2)}\, w_e = \sqrt{2\ln(2)}\, w_0, \tag{A.2}$$

$$w_e = \frac{w_{FWHM}}{2\sqrt{\ln(2)}} = \frac{w_0}{\sqrt{2}}, \tag{A.3}$$

$$w_0 = \frac{w_{FWHM}}{\sqrt{2\ln(2)}} = \sqrt{2}\, w_e. \tag{A.4}$$

A.2.2 Absorptionsquerschnitte und -koeffizienten

Der Absorptionskoeffizient α_k für einen Mehrphotonenprozeß der Ordnung k ist nach Gleichung (2.19) durch

$$\frac{dI}{dz} = -\alpha_k I^k \tag{A.5}$$

definiert. Die Anzahl der Photonen pro Volumenelement wird als Photonenfluß Φ bezeichnet und ist mit der Intensität durch $\Phi = \frac{I}{E_{ph}}$ verknüpft. Dabei gilt analog

$$\frac{d\Phi}{dz} = -\sigma_k n_A \Phi^k, \tag{A.6}$$

wobei σ_k den Absorptionsquerschnitt und n_A die mittlere Dichte der Atome darstellen. Bei der Mehrphotonen-Ionisation werden jeweils k Photonen absorbiert, um ein Elektron in das Leitungsband zu befördern. Es gilt folglich für die erzeugte Elektronendichte n

$$\frac{dI}{dt} = E_{ph}\frac{d\Phi}{dt} = -E_{ph}k\frac{dn}{dt}. \tag{A.7}$$

Die Rate für die Erzeugung von Leitungsbandelektronen durch Mehrphotonen-Ionisation ist somit

$$\frac{dn}{dt} = \frac{\alpha_k}{kE_{ph}} I^k = \frac{\sigma_k n_A}{k}\left(\frac{I}{E_{ph}}\right)^k. \tag{A.8}$$

[1] Full Width at Half Maximum

In [Len98] wurde der gleiche Vorgang durch

$$\frac{dn}{dt} = s_k I^k \tag{A.9}$$

beschrieben. Für die Umrechnung der Koeffizienten zu Vergleichszwecken gelten entsprechend:

$$s_k = \frac{n_A}{kE_{ph}^k}\sigma_k = \frac{\alpha_k}{kE_{ph}}, \tag{A.10}$$

$$\sigma_k = \frac{kE_{ph}^k}{n_A}s_k = \frac{E_{ph}^{k-1}}{n_A}\alpha_k, \tag{A.11}$$

$$\alpha_k = kE_{ph}s_k = \frac{n_A}{E_{ph}^{k-1}}\sigma_k. \tag{A.12}$$

A.3 Datenblätter

Auf den folgenden Seiten sind die Datenblätter der untersuchten Gläser angefügt, die mir freundlicherweise von der Firma Schott zur Verfügung gestellt wurden.

SCHOTT
glass made of ideas

BG 18

Reflexionsfaktor
P_d 0.91
Blasenhaltigkeit
Blasenklasse 2
Chemische Haltbarkeit
FR Klasse 0
SR Klasse 2.0
AR Klasse 2.0

Dichte
ρ [g/cm^3] 2.68
Transformationstemperatur
Tg [°C] 459
Wärmeausdehnung
$\alpha_{-30/+70°C}$ [10^{-6}/K] 7.4
$\alpha_{20/300°C}$ [10^{-6}/K] 8.8
Temperaturkoeffizient
T_k [nm/°C]

Nach DIN 58191 **BP 480/250**
Nach DIN 58191 **KP 605**

Ionengefärbtes Glas

Grenzwerte von τ_i
für Dicke d = 1 mm

Prüfwellenlänge [nm]	Grenzwerte	Wert nach Katalogkurve
350	≥0.30	0.42
405	≥0.65	0.70
514	≥0.88	0.92
633	≤0.25	0.22
694	≤0.03	0.02
1060	$\leq 5\cdot10^{-4}$	$2\cdot10^{-4}$

Brechzahl n

λ [nm]	Element	n
404.7	Hg	1.55
587.6	He	1.54

Farbwerte

	d [mm]	x	y	Y	λ_d [nm]	P_e
A	1	0.361	0.441	61	502	0.20
2856	2	0.309	0.460	46	501	0.31
K	3	0.275	0.472	37	501	0.39
	5	0.233	0.490	26	502	0.49
	1	0.340	0.426	62	500	0.20
3200	2	0.292	0.441	48	500	0.32
K	3	0.260	0.452	38	500	0.39
	5	0.222	0.469	27	500	0.48
	1	0.255	0.335	68	493	0.21
D_{65}	2	0.225	0.341	54	493	0.31
	3	0.206	0.347	45	494	0.38
	5	0.183	0.362	33	495	0.45

Bemerkungen für Anwendungen
Bandpaßfilter
- siehe Abschnitt 6.7.3

Kurzpaßfilter
- siehe Abschnitt 6.7.2

Stand Juni 1997

Transmissionsgrad τ und Reintransmissionsgrad τ_i bei d = 1 mm

λ [nm]	τ	τ_i	λ [nm]	τ	τ_i
200	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	700	0.01	0.01
210	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	710	0.006	0.007
220	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	720	0.004	0.004
230	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	730	0.002	0.002
240	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	740	$9\cdot10^{-4}$	0.001
250	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	750	$7\cdot10^{-4}$	$8\cdot10^{-4}$
260	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	760	$5\cdot10^{-4}$	$5\cdot10^{-4}$
270	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	770	$3\cdot10^{-4}$	$3\cdot10^{-4}$
280	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	780	$2\cdot10^{-4}$	$2\cdot10^{-4}$
290	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	790	$9\cdot10^{-5}$	$1\cdot10^{-4}$
300	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	800	$7\cdot10^{-5}$	$8\cdot10^{-5}$
310	$5\cdot10^{-4}$	$5\cdot10^{-4}$	850	$2\cdot10^{-5}$	$2\cdot10^{-5}$
320	0.03	0.03	900	$1\cdot10^{-5}$	$1\cdot10^{-5}$
330	0.14	0.16	950	$2\cdot10^{-5}$	$2\cdot10^{-5}$
340	0.28	0.31	1000	$5\cdot10^{-5}$	$6\cdot10^{-5}$
350	0.38	0.42	1060	$2\cdot10^{-4}$	$2\cdot10^{-4}$
360	0.45	0.50	1100	$5\cdot10^{-4}$	$5\cdot10^{-4}$
370	0.50	0.55	1200	0.003	0.003
380	0.55	0.60	1300	0.02	0.02
390	0.59	0.64	1400	0.05	0.06
400	0.62	0.68	1500	0.14	0.15
410	0.65	0.72	1600	0.25	0.28
420	0.68	0.75	1700	0.40	0.44
430	0.71	0.78	1800	0.51	0.56
440	0.73	0.81	1900	0.60	0.66
450	0.76	0.83	2000	0.68	0.75
460	0.78	0.85	2100	0.70	0.77
470	0.79	0.87	2200	0.71	0.78
480	0.81	0.89	2300	0.70	0.77
490	0.82	0.90	2400	0.72	0.79
500	0.83	0.91	2500	0.69	0.76
510	0.83	0.92	2600	0.62	0.68
520	0.83	0.92	2700	0.54	0.59
530	0.83	0.91	2800	0.06	0.07
540	0.81	0.89	2900	0.004	0.004
550	0.79	0.86	3000	$9\cdot10^{-4}$	0.001
560	0.75	0.82	3200	$4\cdot10^{-4}$	$4\cdot10^{-4}$
570	0.69	0.76	3400	$3\cdot10^{-4}$	$3\cdot10^{-4}$
580	0.62	0.69	3600	$6\cdot10^{-4}$	$6\cdot10^{-4}$
590	0.55	0.60	3800	$9\cdot10^{-4}$	0.001
600	0.46	0.51	4000	$4\cdot10^{-4}$	$4\cdot10^{-4}$
610	0.37	0.41	4200	$9\cdot10^{-5}$	$1\cdot10^{-4}$
620	0.29	0.32	4400	$2\cdot10^{-4}$	$2\cdot10^{-4}$
630	0.22	0.24	4600	$4\cdot10^{-4}$	$4\cdot10^{-4}$
640	0.16	0.18	4800	$4\cdot10^{-4}$	$4\cdot10^{-4}$
650	0.11	0.12	5000	$5\cdot10^{-4}$	$5\cdot10^{-4}$
660	0.07	0.08	5200	$9\cdot10^{-5}$	$1\cdot10^{-4}$
670	0.05	0.05			
680	0.03	0.03			
690	0.02	0.02			

SCHOTT

MATERIAL SAFETY DATA SHEET

Glass Type: BG18

SECTION I GENERAL INFORMATION

Information furnished by:	SCHOTT GLAS
Address:	Hattenbergstr. 10, 55122 Mainz, Germany
Telephone Number:	+49 (0) 6131 / 66-2747
Product Name(s):	**BG18**
Chemical Name:	Inorganic Glass
C.A.S. Number:	65997-17-3
Date effective:	July 28, 2003

SECTION II INGREDIENTS DATA

CHEMICAL NAME	PERCENTAGE BY WEIGHT	REG.* (Y/N)	CAS#	OSHA (PEL)	ACGIH (TLV)	CARC. (Y/N)
Phosphorous Oxide	70 - 80	N	1314-56-3	N/A	N/A	N
Aluminum Oxide	1 - 10	Y	1344-28-1	15 mg/m³	10 mg/m³	N
Copper Oxide	1 - 10	Y	1317-38-0	1 mg/m³	1 mg/m³	N
Magnesium Oxide	1 - 10	Y	1309-48-4	10 mg/m³	10 mg/m³	N
Potassium Oxide	1 - 10	N	12136-45-7	N/A	N/A	N
Boron Oxide	1 - 10	Y	1303-86-2	15 mg/m³	10 mg/m³	N
Sodium Oxide	1 - 10	N	1313-59-3	N/A	N/A	N
Barium Oxide	< 1	Y	1304-28-5	0.5 mg/m³	0.05 mg/m³	N
Zinc Oxide	< 1	Y	1314-13-2	5 mg/m³ (fume)	10 mg/m³ (dust)	N
Lithium Oxide	< 1	Y	12057-24-8	N/A	N/A	N
Silica	< 1	Y	14808-60-7	0.1 mg/m³	0.1 mg/m³	N
Calcium Oxide	< 1	Y	1305-78-8	5 mg/m³	2 mg/m³	N
Cerium Oxide	< 1	N	1306-38-3	N/A	N/A	N
Arsenic Trioxide	< 1	Y	1327-53-3	10 µg/m³	200 µg/m³	Y

* Regulated as per lists: OSHA 29CFR 1910 Subpart Z: ACGIH: NTP and IARC

SECTION III PHYSICAL DATA

Boiling point:	not applicable
Vapor pressure:	not applicable
Vapor density:	not applicable
Solubility in water:	not applicable
Specific gravity:	2.68 g/cm³
Melting point:	482 °C
Physical state:	solid with a density of 2.68 g/cm³
Appearance and odor:	various forms and shapes with no odor

SCHOTT

MATERIAL SAFETY DATA SHEET

Glass Type: BG18

SECTION IV FIRE AND EXPLOSION HAZARD DATA

Flash point:	not applicable
Auto ignition temperature:	not applicable
Flammable limits/% volume in air:	not applicable
Extinguishing media:	This material is non-combustible.
Special fire fighting procedures:	Use extinguishing media that is appropriate for the classification of the surrounding fire. Inorganic glass is non-combustible.
Unusual fire and explosion hazards:	There is a possibility of flying glass fragments if hot glass comes in contact with water or carbon dioxide extinguishing media.

SECTION V HEALTH HAZARD DATA

Route(s) of Entry: Effects of Overexposure

Inhalation:	Acute:	Respiratory irritation. Chronic: Possible pneumoconiosis effects.
Ingestion:	Ingestion may cause vomiting, diarrhea, depressed circulation and in severe cases shock, coma, paralysis and cyanosis.	
Skin:	Glass dust may cause irritation. Arsenic has been known to cause itching, pigmentation and cancerous changes of the skin.	
Eye:	May cause irritation.	
First Aid:	Inhalation:	Remove to fresh air. Seek medical attention.
	Ingestion:	Seek medical attention.
	Skin:	Wash with soap and water. Get medical attention if irritation persists.
	Eye:	Flush well with running water. Get medical attention if irritation persists.

SECTION VI SPILL, LEAK AND DISPOSAL

Spill or leak procedures:	No special precautions.
Waste disposal:	Follow Federal, State and Local Regulations.

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MATERIAL SAFETY DATA SHEET

Glass Type: BG18

SECTION VII SPECIAL PROTECTION INFORMATION

Engineering controls:	Use local exhaust ventilation, hood or equipment enclosure to avoid dispersal of fibrous or other glass particulates into the workplace air.
Personal protective equipment:	Respiratory - If glass dust or particulates are above the OSHA permissible exposure limits use a NIOSH approved respirator for dust and fibers. Eye protection - Industrial safety glasses that meet ANSI Z 87 standards. Protective gloves - Recommend gloves for protection from sharp edges.

SECTION VIII SPECIAL PRECAUTIONS AND COMMENTS

Reactivity:	This is stable material. Glass is inert to many chemicals, but may react to hot, strong alkaline solutions and with hydrofluoric, fluosilicic and phosphoric acids. Hazardous Decomposition or Byproducts: May emit metal oxide fumes when heated to high temperatures.
Comments:	Inorganic glass is an amorphous, inorganic, usually transparent or translucent substance consisting of a mixture of silicates or sometimes borates or phosphates formed by fusion of silica and various types of oxides with a flux and a stabilizer, into a mass that cools to a rigid condition without crystallization.

SCHOTT

MATERIAL SAFETY DATA SHEET

SECTION I GENERAL INFORMATION

Information furnished by:	SCHOTT GLAS
Address:	Hattenbergstr. 10, 55122 Mainz, Germany
Telephone Number:	+49 (0) 6131 / 66-2168
Product Name(s):	**PK50**
Chemical Name:	Inorganic Glass
C.A.S. Number:	65997-17-3
Date effective:	October 15, 2003

SECTION II INGREDIENTS DATA

CHEMICAL NAME	PERCENTAGE BY WEIGHT	REG.* (Y/N)	CAS#	OSHA (PEL)	ACGIH (TLV)	CARC. (Y/N)
Aluminum Oxide	1 - 10	Y	1344281	15 mg/m³	10 mg/m³	N
Boron Oxide	1 - 10	Y	1303862	15 mg/m³	10 mg/m³	N
Magnesium Oxide	1 - 10	Y	1309484	10 mg/m³	10 mg/m³	N
Phosphorous Oxide	60 - 70	N	1314563	N/A	N/A	N
Potassium Oxide	10 - 20	N	12136457	N/A	N/A	N
Arsenic Trioxide	1 - 10	Y	1327533	10 µg/m³	200 µg/m³	Y

* Regulated as per lists: OSHA 29CFR 1910 Subpart Z: ACGIH: NTP and IARC

SECTION III PHYSICAL DATA

Boiling point:	not applicable
Vapor pressure:	not applicable
Vapor density:	not applicable
Solubility in water:	not applicable
Specific gravity:	2,59 g/cm³
Melting point:	496 °C
Physical state:	solid with a density of 2,59 g/cm³
Appearance and odor:	various forms and shapes with no odor

SECTION IV FIRE AND EXPLOSION HAZARD DATA

Flash point:	not applicable
Auto ignition temperature:	not applicable
Flammable limits/% volume in air:	not applicable
Extinguishing media:	This material is non-combustible.
Special fire fighting procedures:	Use extinguishing media that is appropriate for the classification of the surrounding fire. Inorganic glass is non-combustible.
Unusual fire and explosion hazards:	There is a possibility of flying glass fragments if hot glass comes in contact with water or carbon dioxide extinguishing media.

SECTION V HEALTH HAZARD DATA

Route(s) of Entry: Effects of Overexposure

Inhalation:	Acute:	Respiratory irritation. Chronic: Possible pneumoconiosis effects.
Ingestion:	Ingestion may cause vomiting, diarrhea, depressed circulation and in severe cases shock, coma, paralysis and cyanosis.	
Skin:	Glass dust may cause irritation. Arsenic has been known to cause itching, pigmentation and cancerous changes of the skin.	
Eye:	May cause irritation.	
First Aid:	Inhalation:	Remove to fresh air. Seek medical attention.
	Ingestion:	Seek medical attention.
	Skin:	Wash with soap and water. Get medical attention if irritation persists.
	Eye:	Flush well with running water. Get medical attention if irritation persists.

SECTION VI SPILL, LEAK AND DISPOSAL

Spill or leak procedures:	No special precautions.
Waste disposal:	Follow Federal, State and Local Regulations.

SECTION VII SPECIAL PROTECTION INFORMATION

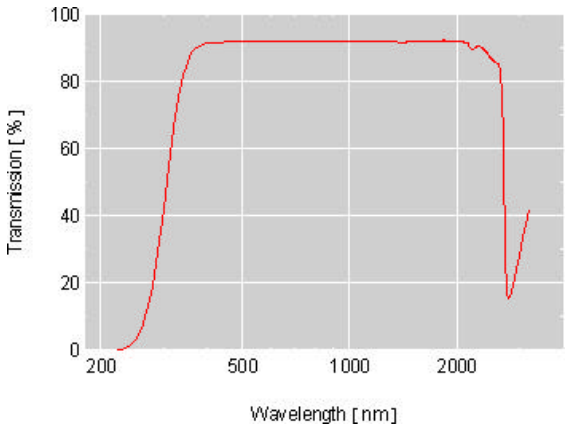
Engineering controls:	Use local exhaust ventilation, hood or equipment enclosure to avoid dispersal of fibrous or other glass particulates into the workplace air.
Personal protective equipment:	Respiratory - If glass dust or particulates are above the OSHA permissible exposure limits use a NIOSH approved respirator for dust and fibers. Eye protection - Industrial safety glasses that meet ANSI Z 87 standards. Protective gloves - Recommend gloves for protection from sharp edges.

SECTION VIII SPECIAL PRECAUTIONS AND COMMENTS

Reactivity:	This is stable material. Glass is inert to many chemicals, but may react to hot, strong alkaline solutions and with hydrofluoric, fluosilicic and phosphoric acids. Hazardous Decomposition or Byproducts: May emit metal oxide fumes when heated to high temperatures.
Comments:	Inorganic glass is an amorphous, inorganic, usually transparent or translucent substance consisting of a mixture of silicates or sometimes borates or phosphates formed by fusion of silica and various types of oxides with a flux and a stabilizer, into a mass that cools to a rigid condition without crystallization.

Material data of BK7 Schott glass

Transmission Spectrum of BK7
Schott glass windows (3 mm thickness)



Refractive index n and internal transmittance t_i

Wavelength [nm]	n	t_i (t=5mm)
365	1.53627	0.994
404.7	1.53024	0.998
435.8	1.52668	0.999
480	1.52283	0.999
486.1	1.52238	0.999
546.1	1.51872	0.999
587.6	1.5168	0.999
589.3	1.51673	0.999
632.8	1.51509	0.999
643.8	1.51472	0.999
656.3	1.51432	0.999
706.5	1.51289	0.999
852.1	1.50980	0.999
1014	1.50731	0.999
1060	1.50669	0.999
1529	1.50091	0.997

Applications

- Plane and curved mirror substrates
- Windows and spherical lenses
- All with any type of coating (HR, PR, AR) for the wavelength range given in the table
- All transmittive components are selected to be free of bubbles and inclusions

Properties

- High transmission from VIS to NIR
- Very good homogeneity

Optical Data

- Homogeneity (dn):
  - Standard: < 2 x10^{-5}
  - On request: down to 1 x 10^{-6}
- Max. bubble diameter: < 0.1 mm
- Max. cross section of bubbles in 100 cm³ of glass: < 0.03 mm²
- Max. cross section of inclusions in 100 cm³ of glass: < 0.03 mm²

Mechanical Data

- Density: 2.51 g/cm³
- Young modulus: 82 GPa
- Poisson ratio: 0.206

Thermal Data

- Thermal linear expansion coefficient
  - -30...+70°C: 7.1 x 10^{-6} K^{-1}
  - +20...+300°C: 8.3 x 10^{-6} K^{-1}
- Specific heat capacity: 858 J/(kg•K)
- Thermal conductivity: 1.114 W/(m•K)
- Melting point: 559 °C