Application of sapphire bonding for suspension of cryogenic mirrors

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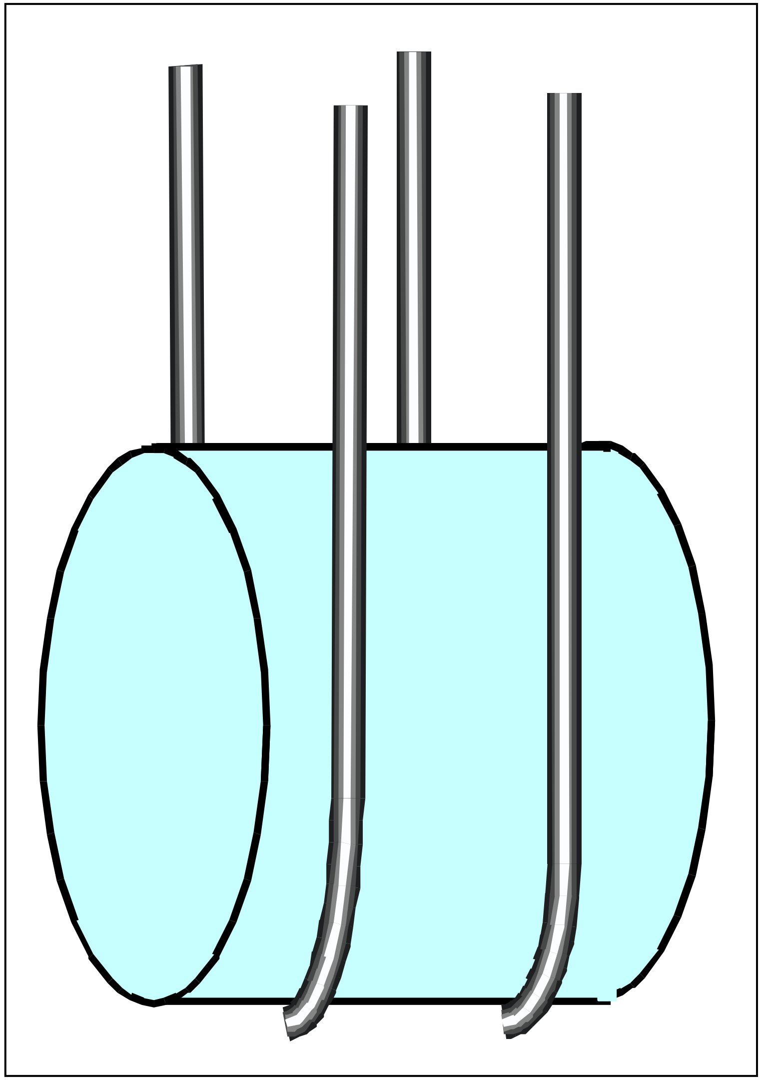
Contents and current results

- Sapphire mirror suspension of LCGT
- Comparison with direct bonding and chemical bonding
  - Thermal conductance 4.2 [K] - 300 [K]
  - Shear strength at 300 [K]

- Additional thermal resistance
  - No additional resistance from direct bonding
  - Finite resistance was found from chemical bonding
- Shear strength of bonding
  - 28.4 [MPa] for direct bonding
  - 6.53 [Mpa] for chemical bonding

Basic Configuration of Cryogenic Mirror



Suspension of CLIO

Mirror

Al_2O_3 Single Crystal
(=Sapphire)

Suspension

Sapphire Single Crystal Fibre.
Elastically deformed along the cylindrical surface.

⇨Heat path for conduction cooling.
⇨Low loss mechanical support.

T.Uchiyama et.al, Phys. Lett. A242 (1998) 211.

LCGT needs ϕ1.8mm Fibres (or Rods)

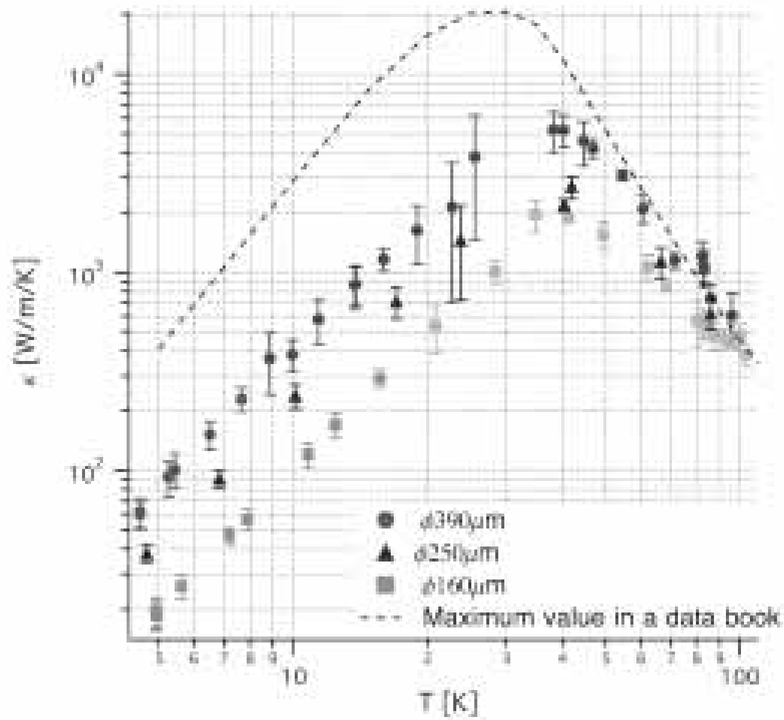


Fig. 3. Measurement results of the thermal conductivity of mono-crystalline sapphire fibers. The closed circles, triangles and squares are the measured thermal conductivity of fibers of ⌀390 μm, ⌀250 μm and ⌀160 μm, respectively. The dashed line shows the maximum thermal conductivity of sapphire reported in a data book [10] (⌀2.5 mm sample).

T.Tomaru 他, Phys.Lett. A301(2002)215.

$\dot{q}$ ~ 1 [W] -> ϕ1.8 [mm]

* α~40 ppm/cm

∵ Thermal Conductivity κ in Sapphire Fibre

$\kappa = C_v v_c l / 3$

C_v : Specific Heat

v_c : velocity of carrier

l : mean free path ~(Diameter of Fibre) -> Size effect

(Heat Transfer) $\propto l^3$ (T<20[K])

Cryogenic mirror for LCGT

Mirror

Al_2O_3 Single Crystal (=Sapphire)

Size: ϕ250mm x 180mm

Operating Temperature: 20K

Suspension

Al_2O_3 Single Crystal Fibre (or Rod)

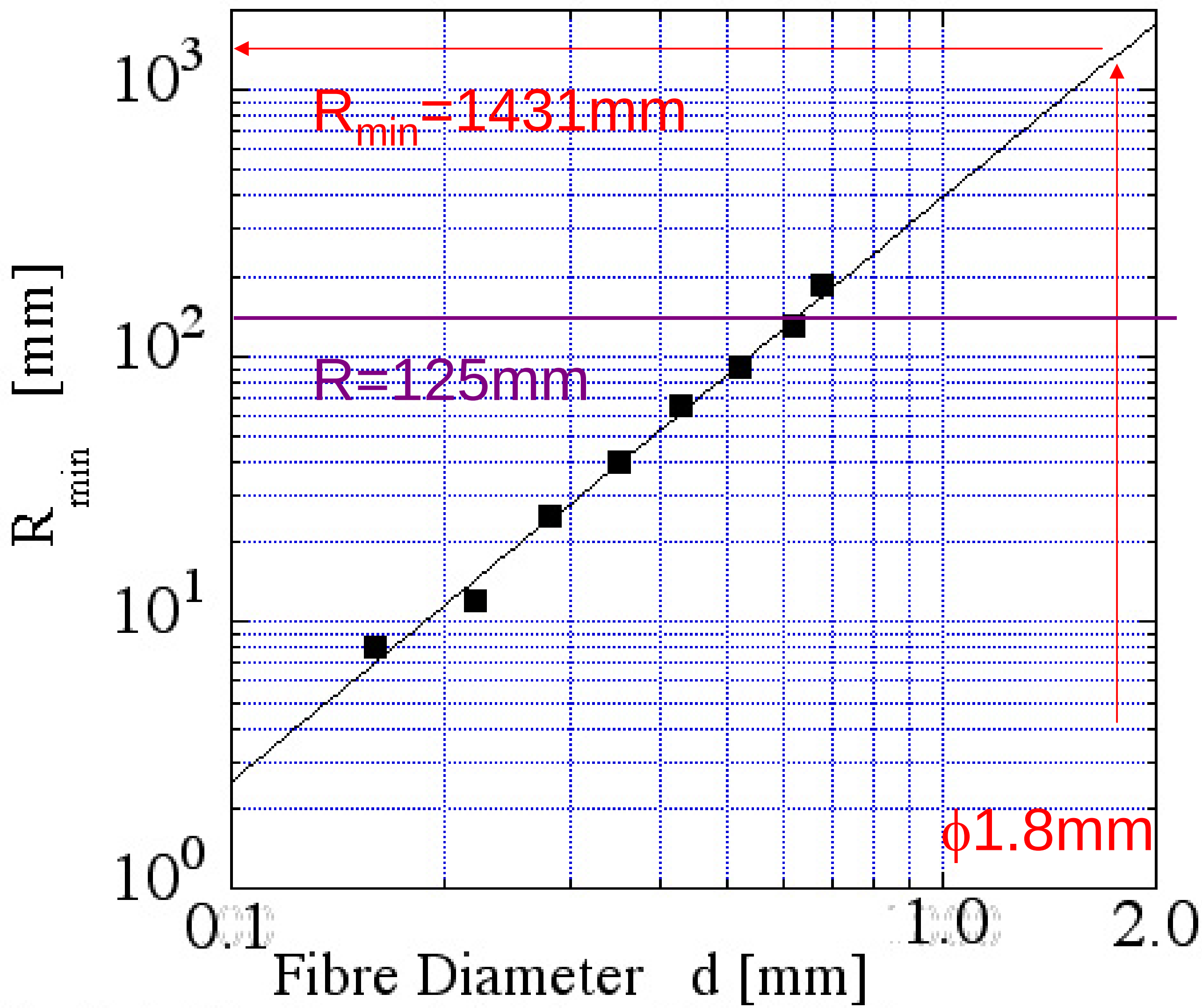
Diamter: ϕ1.8mm

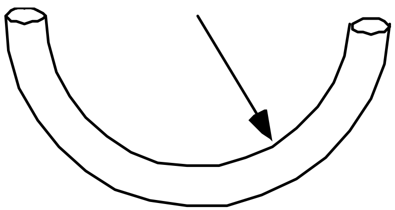
Length: 500mm

Number: 2 pairs (or 4 rods)

Minimum Bending Radius of Sapphire Fibre

$$R_{min} = 2.55 \text{ mm} * (d / 0.1 \text{ mm})^{2.19}$$





(From Fig.2 of Ling Tong et al., Appl. Opt. vol.39 (2000) 494.)

FibreBendRadius.kgd

Suspension of LCGT

It is not applicable of ϕ1.8 mm rod to deform elastically along the cylindrical surface of the mirror .

Possible Candidates for making suspension

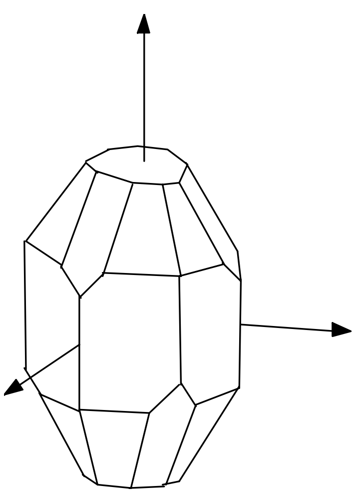
- Mechanical connection
- Plastic deformation of rod
- Shape-controlled growth of crystal
- Sapphire-sapphire bonding
  - ♡ Direct bonding (adhesion free)
  - ♣ Chemical (Sodium Silicate, Hydroxide-catalysis)
  - ◊ Glue
  - ♤ Fusion, Welding, Brazing, Soldering, ….

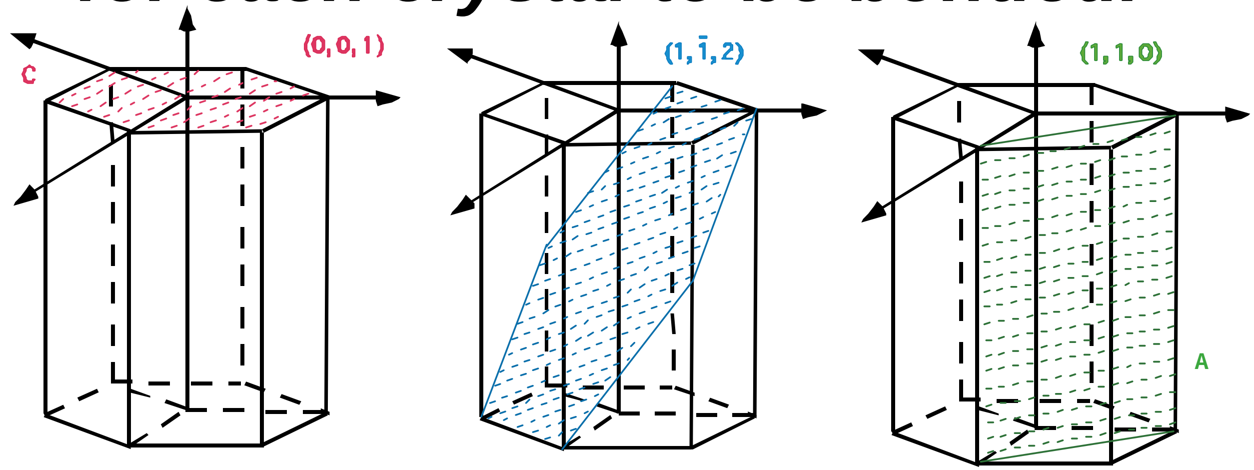
Direct Bonding of Sapphire

Bonding process

1.Polishing ~ optical contact
2.Heat treatment : solid phase diffusion bonding
1300~1400 °C

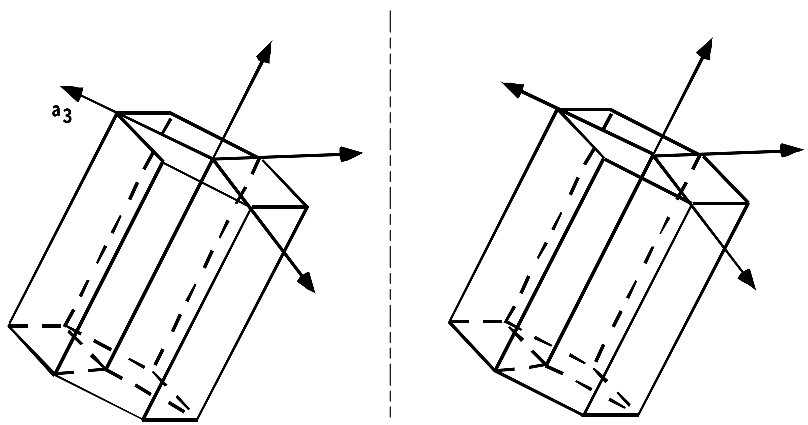
Choose proper lattice plane
for each crystal to be bonded.



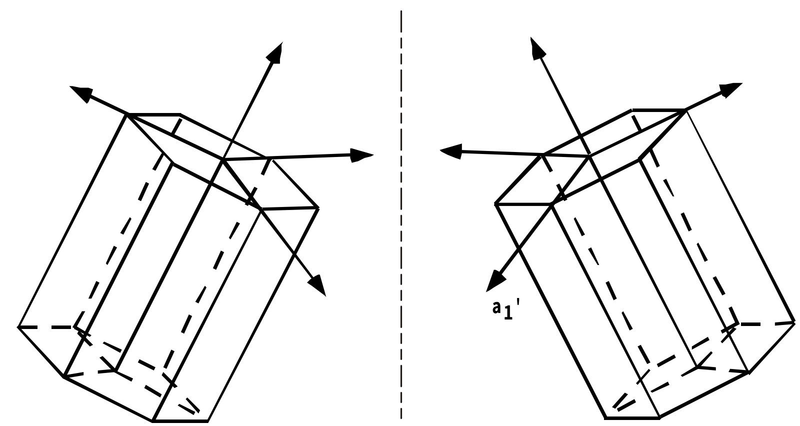


Condition of bonding boundary

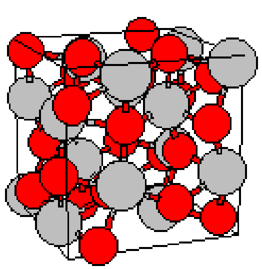
Translation of Bravais lattice



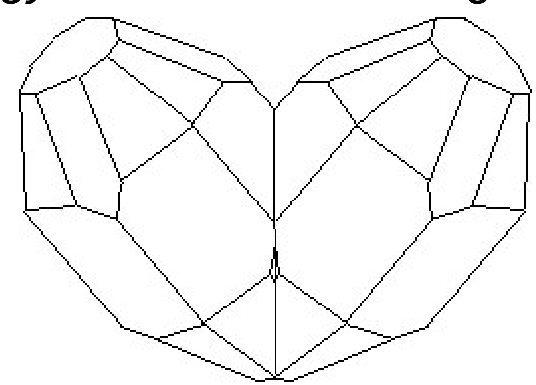
Reflection of Bravais lattice



Equivalent to a single crystal



Analogy of coherent twinning boundary



Measured properties

- Thermal conductance
- Mechanical strength

Chemical Bonding

ϕ10mm x 30mm x 2

Nihongaishi Co.

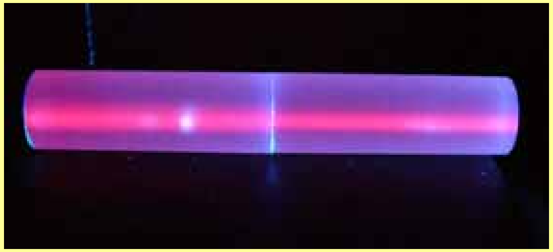
C.Taylor and L.Conti
+ Stanford Univ.

Direct Bonding

ϕ10mm x 30mm x 2

Nihongaishi Co.

Japan Cell



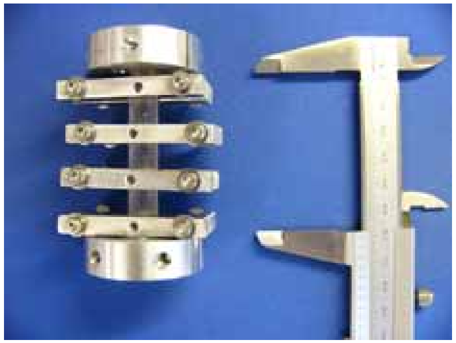
Direct Bonding

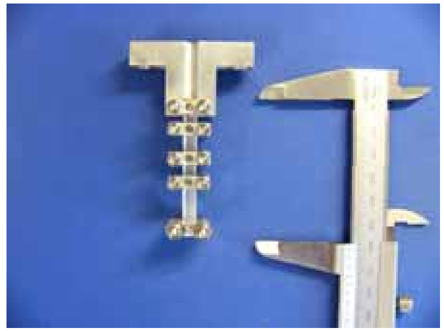
□5mm x 30mm x 2

CSI HEMEX

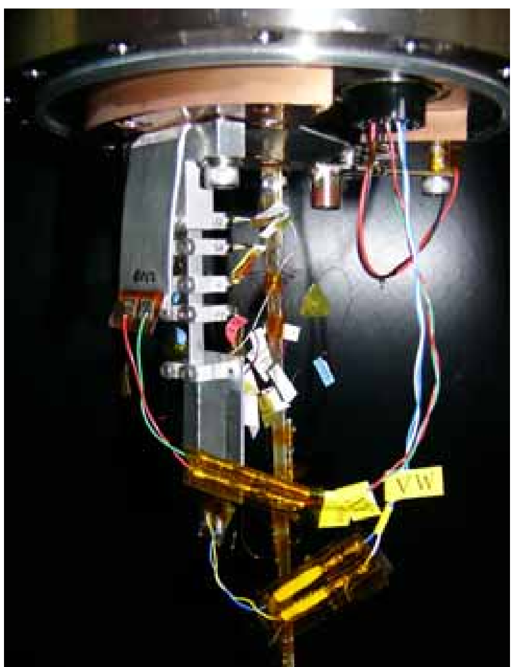
Onyx Optics

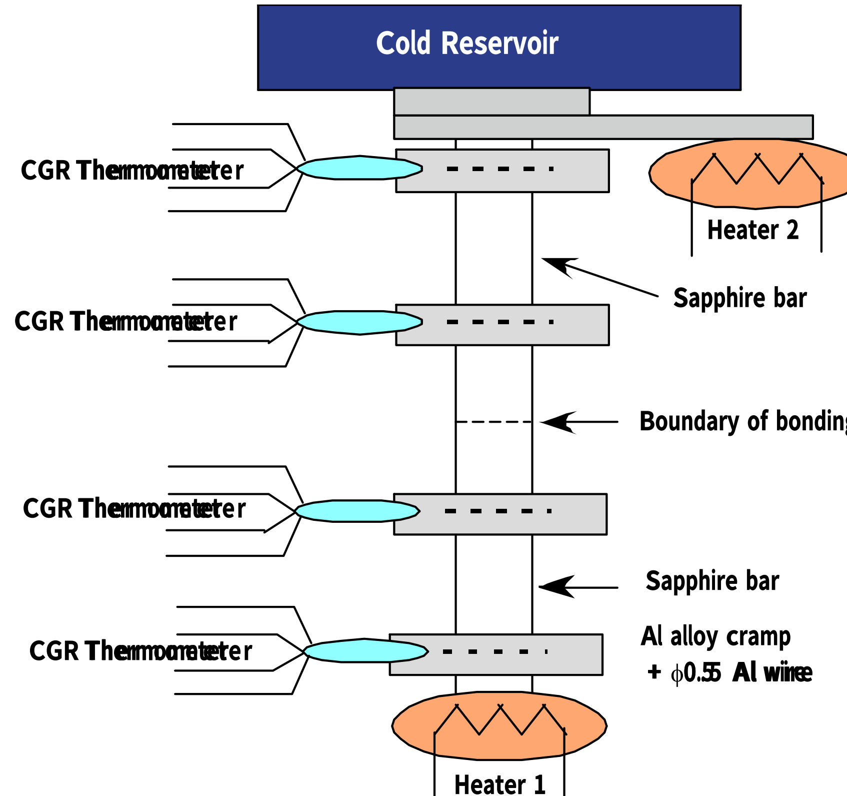
Measurement of Thermal Conductance





ϕ10 x 60 Sample □5 x 60 Sample



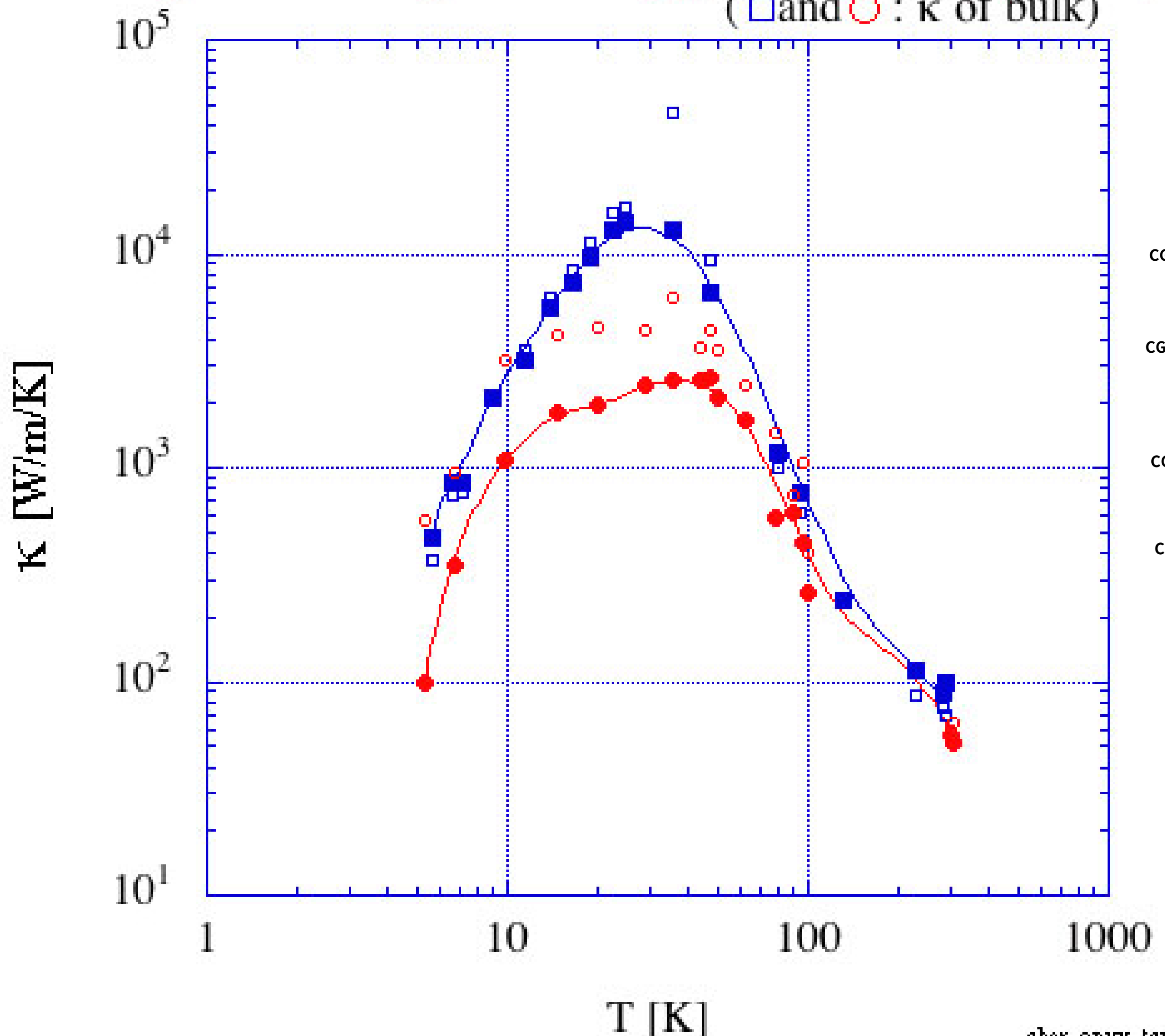


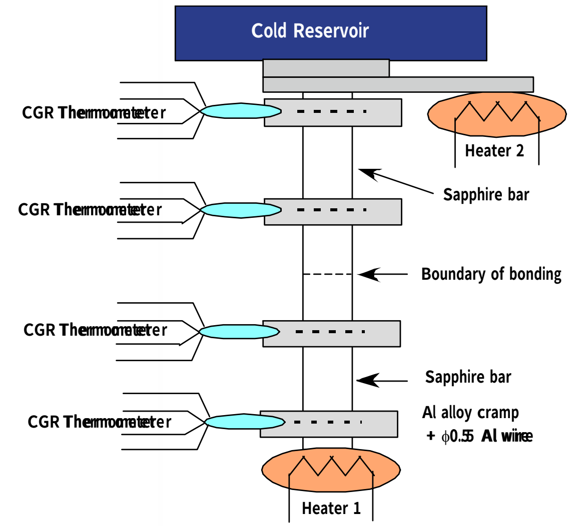
Thermal Conductivity of Bonded Sapphires

■ : Adhesion Free Bonding (Onyx Inc.), 5x5x60, CSI Hemex

● : Hydroxide-catalysis Bonding,grade unknown, ϕ10x60,

(□ and ○ : κ of bulk)

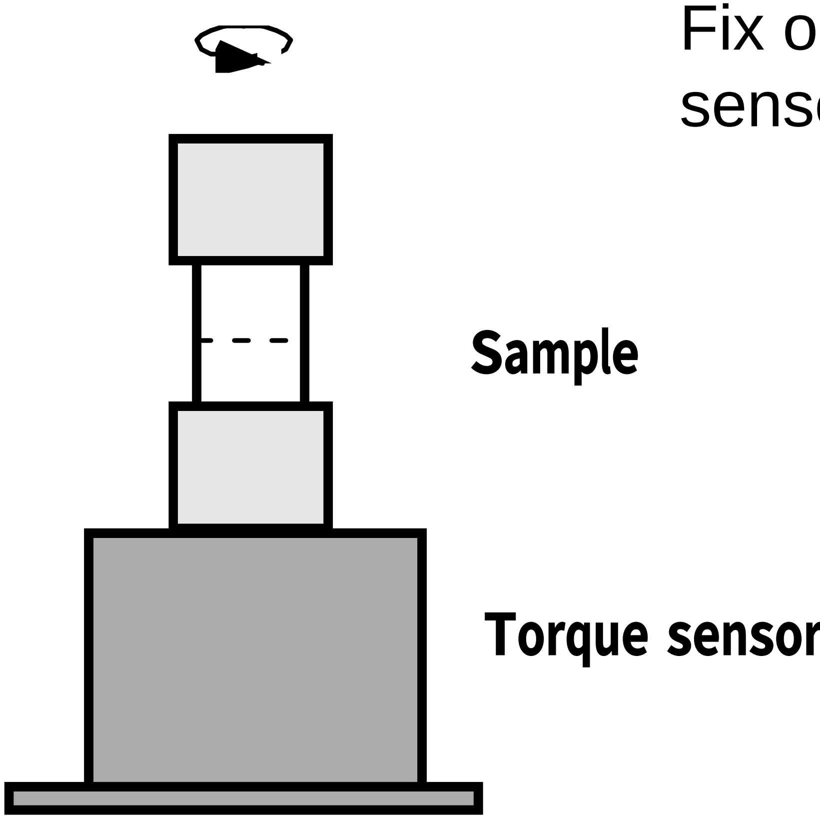


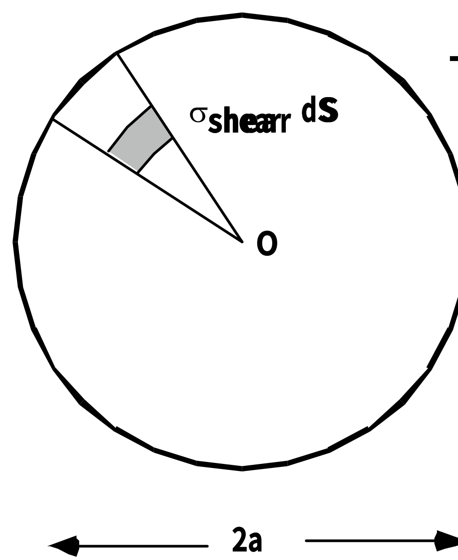


char_onyx_tcm_v2.kgd

Measurement of shear strength

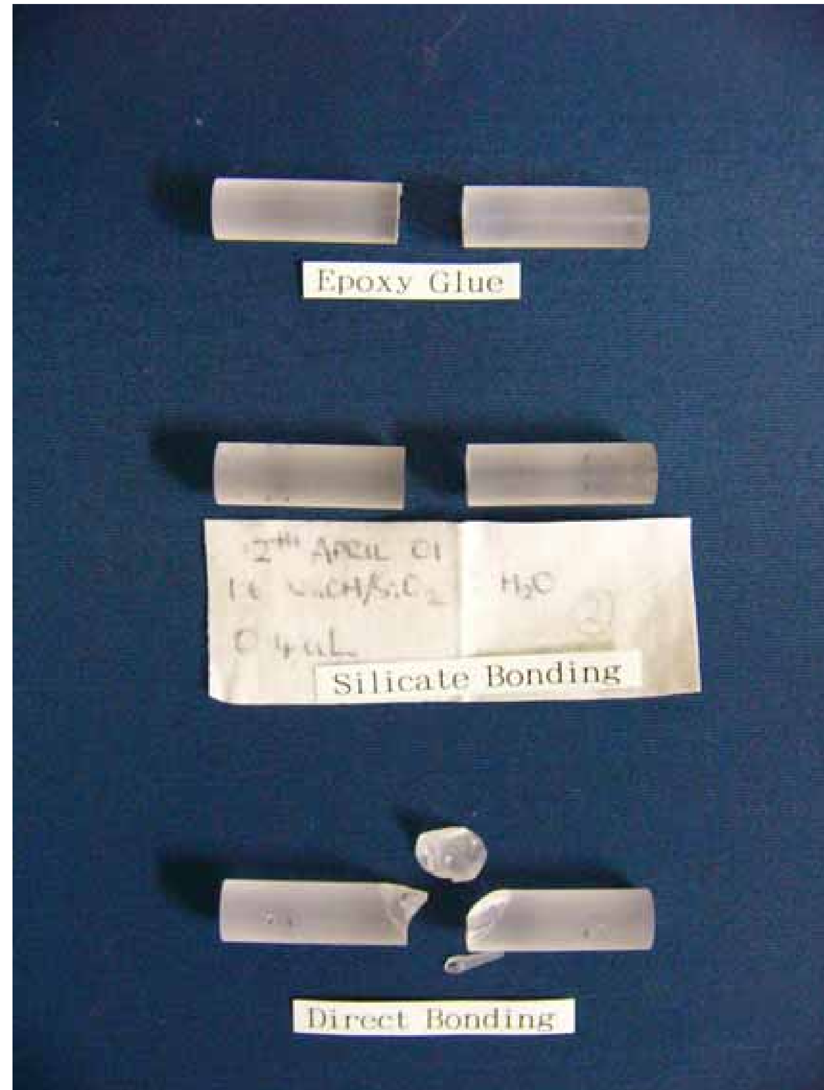
Fix one end of the sample on the sensor, then put torque.





$$T = \frac{2\pi\sigma_{shear}a^3}{3}$$

Photos of strength test (300K)



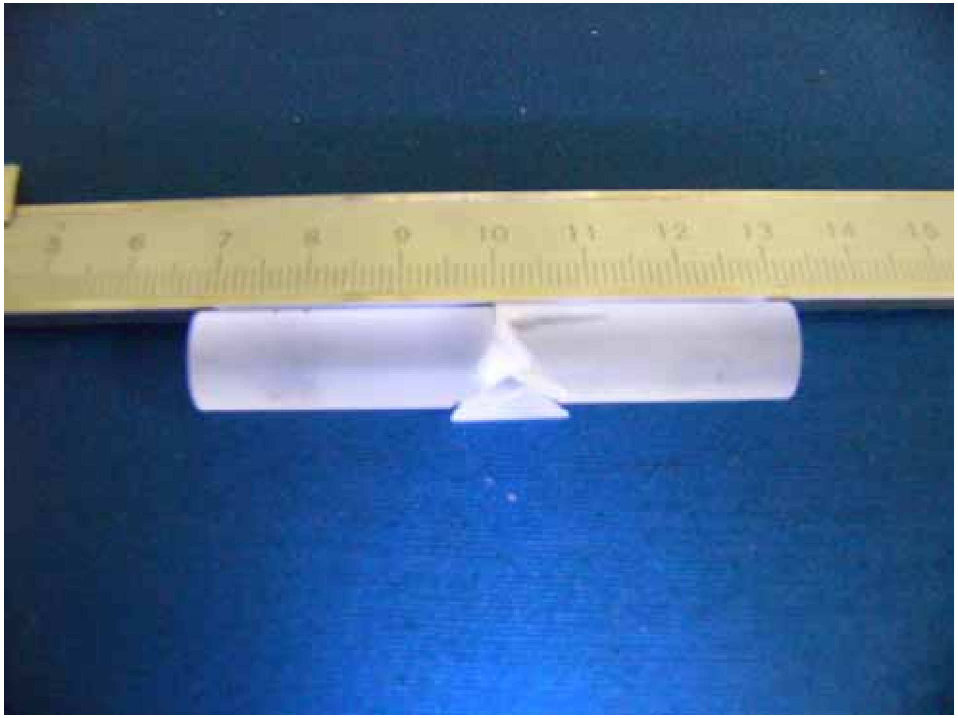
Comparison of strength (300K)

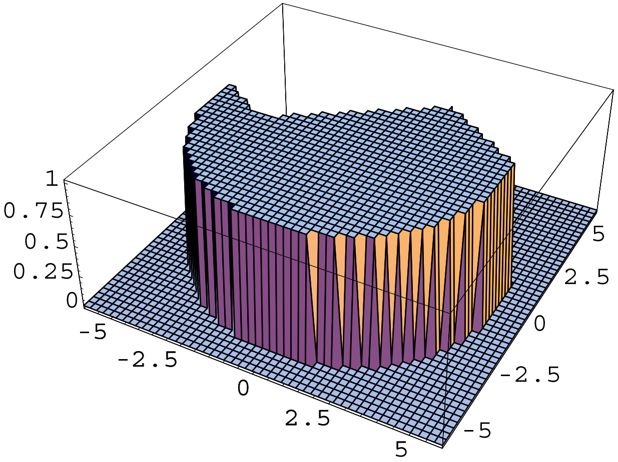
	Direct Bonding	Silicate Bonding	Epoxy Glue
Max. Torque [N・m]	4.69	1.71	0.608
σ_{shear} [Mpa]	28.4*	6.53	2.32
Breaking	Substrate~2/3 Boundary~1/3	Along the boundary	Along the boundary

* From substrate breaking

- D.B. T~1700 [K]
- H.-C.B. NaOH/SiO_2:H_2O=1:6 0.2μL
- Epoxy Glue : 20℃ 24hours cure

Correction of σ_{shear} by breaking area



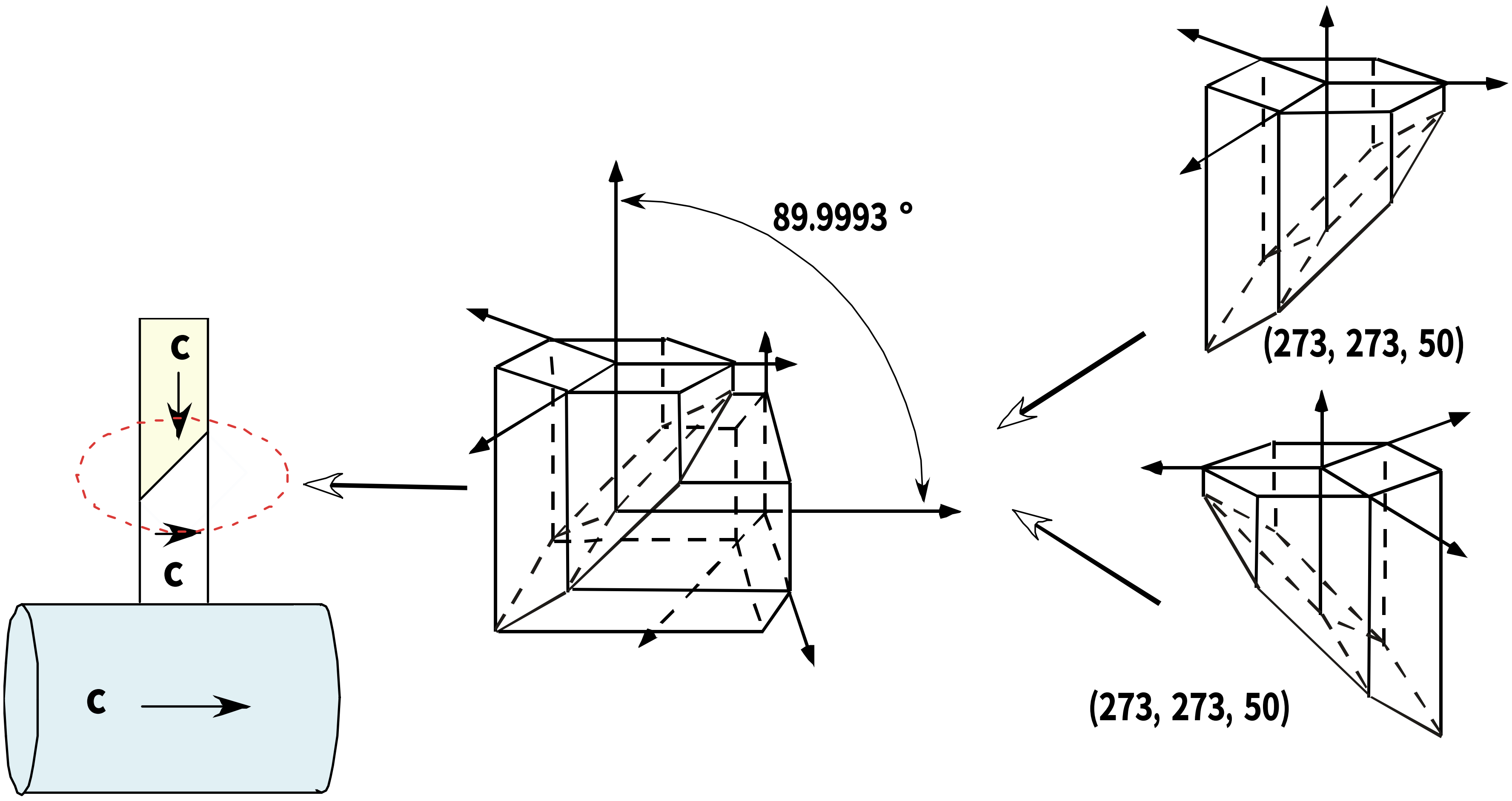


Required area for LCGT mirror

Table 1: Comparison with Shear Strength of Sapphire Bonding

	Direct Bonding	Silicate Bonding	Epoxy Glue
σ_{shear}	28.4 [MPa]	6.53 [MPa]	2.32 [MPa]
$A_{Mg/4}$	2.53 [mm^2]	11.0 [mm^2]	30.9 [mm^2]

Example of suspension by direct bonding



Issues

- Cryogenic measurements of strength.
- Thermal cycles/ aging.
- Mechanical loss measurement.
- Quality control.
- Connection to SPI
- Interference with mirror polishing/coating process?
- Maintenance

Summary

- Chemical bonding show some thermal resistance.
- No additional thermal resistance from direct bonding.
- Shear strength 28.4 [MPa] for direct bonding , 6.53 [Mpa] for chemical bonding.