Adhesive-Free Edge-Bond Single Crystal Silicon Mirror Substrate

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Outline

- ***Introduction***

— *Adhesive-Free Bond (AFB®) technology and its applications*

- ***Edge-bond single crystal mirror substrate***

— *Phase I program overview and progress*

— *Roadmap toward meter-level SC-Si mirrors*

- ***Mechanical and thermal test results in AFB® composites***

— *Equi-biaxial flexural strength tests in AFB® Sapphire composite*

— *Equi-biaxial flexural strength tests in AFB® SC-Si composite*

— *Thermal test in AFB® YAG composites*

- ***Summary***

Adhesive-Free Bond (AFB®) Technology

- ***AFB® Generic Process Schematic***

Surface preparation — Flatness, Cleanliness

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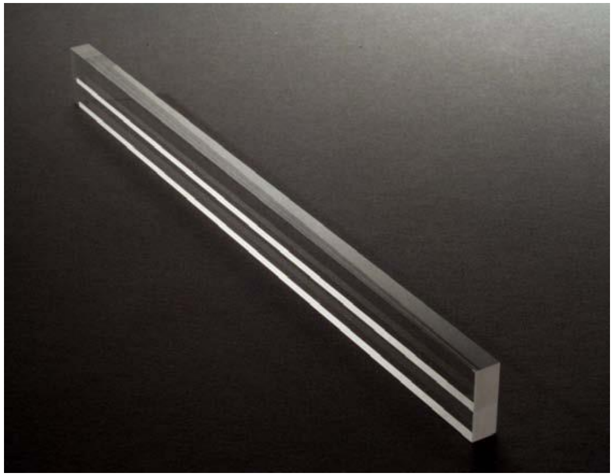
Optical Contact — Temporary bond

↓

Heat Treatment — Permanent bond



- ***Advantages***

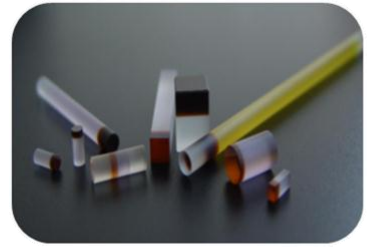
— ***Allows crystal and glass materials to be joined at moderate temperatures without adhesives***

— ***Results in comparable optical, mechanical and thermal properties to that of non-bonded materials***

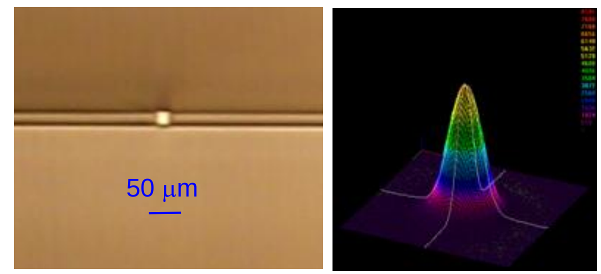
— ***Enables higher efficiency, more compact, and higher power solid state laser and photonic devices***

Applications of AFB® Technology

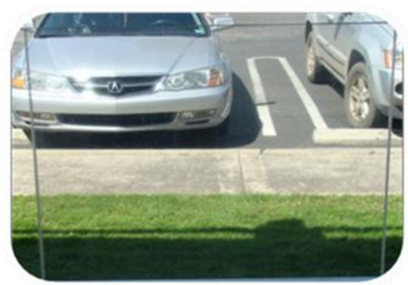
- ***Laser components***
  - *Un-doped end-capped rods and slabs*
  - *Disks and microchips*
  - *Waveguides and crystalline fiber waveguides*
  - *Beam splitters and polarizers*
  - *Walk-off compensated nonlinear optics*
- ***Edge-bond larger size windows***
  - *Sapphire, Spinel, Alon, YAG, Silicon, ……*
- ***Precision measurements***
  - *Refractive index ~ 10^{-6}*
  - *Thermal conductivity*



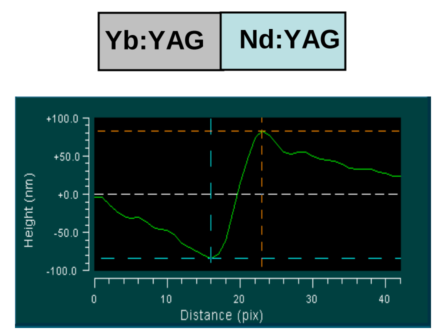
Nd:YAG/Cr^{4+}:YAG microchips and rods



20-µm core size Tm:YAG CFW and waveguide mode



Edge-bonded ALON window



OPD between 1% Yb:YAG and 0.2% Nd:YAG, $\Delta n = 3.4 \times 10^{-5}$.

Single Crystal Silicon Mirror

Advantages

— ***Simple fabrication process and low cost compared with Beryllium and SiC mirrors***

— ***Excellent surface figure and surface finish: rms < 0.5 nm***

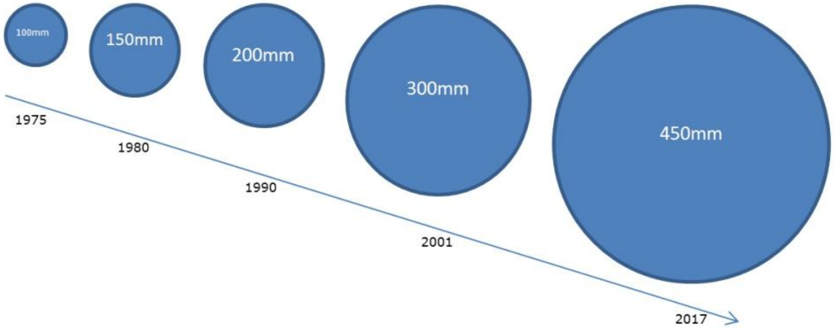
— ***Excellent resistance to thermal distortion, especially at cryogenic temperatures due to high homogeneity; low internal stress; low CTE ; and high thermal conductivity***

V. T. Bly, et.al., Proc. of SPIE 8486, 84860P (2012)

Major challenge

— ***Limited size: ~ 450 mm***

A Jams Webb Space Telescope primary mirror segment
http://www.jwst.nasa.gov/images_mirror41.html



Silicon wafer size history
http://anysilicon.com/does-size-matter-understanding-wafer-size

Onyx Optics Phase I Overview

- ***Manufacturing process development***
  - *Edge bond hexagonal composite from 6 equilateral triangles for ϕ >10" , Thk > 1.5"*
  - *Demonstration of technique roadmap toward meter-level SC-Si mirrors*
  - *Precision polishing large Si substrates*

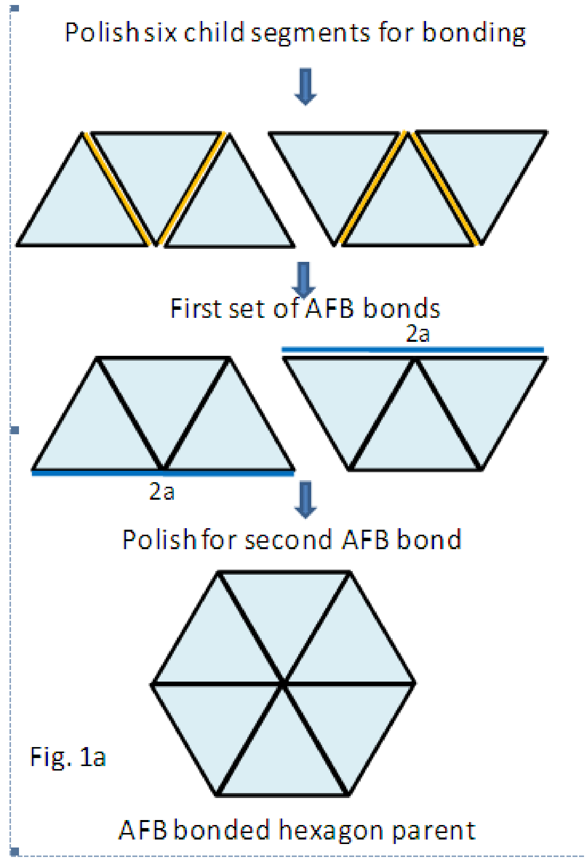
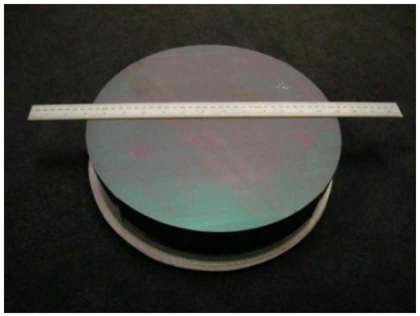


Fig. 1a

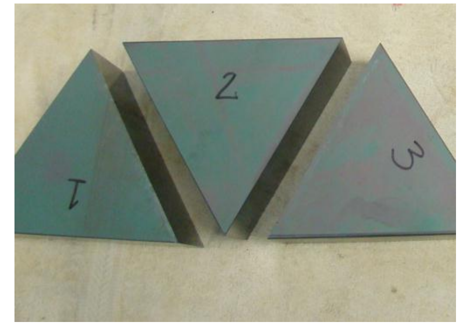
- ***Characterization of AFB® interfaces***
  - *Optical characterization: Inspect bond interfaces by transmitted wavefront at 1.55 µm*
  - *Thermal characterization: Measure heat transfer between bonded interfaces of SC-Si at room temperature and liquid nitrogen*
  - *Mechanical characterization: Equi-biaxial fracture strength of composite disks;*

Progress of SC-Si Hexagonal Composite



Starting SC-Si disk
ϕ ~ 12 ¾", Thk ~ 2 ¾"

Cut into 6 equilateral triangles

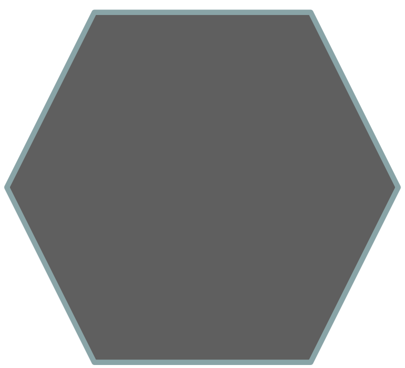


Edges prepared for bonding

Edge bond into 2 trapezoids
W ~ 12 1/3", h ~ 5 1/3"

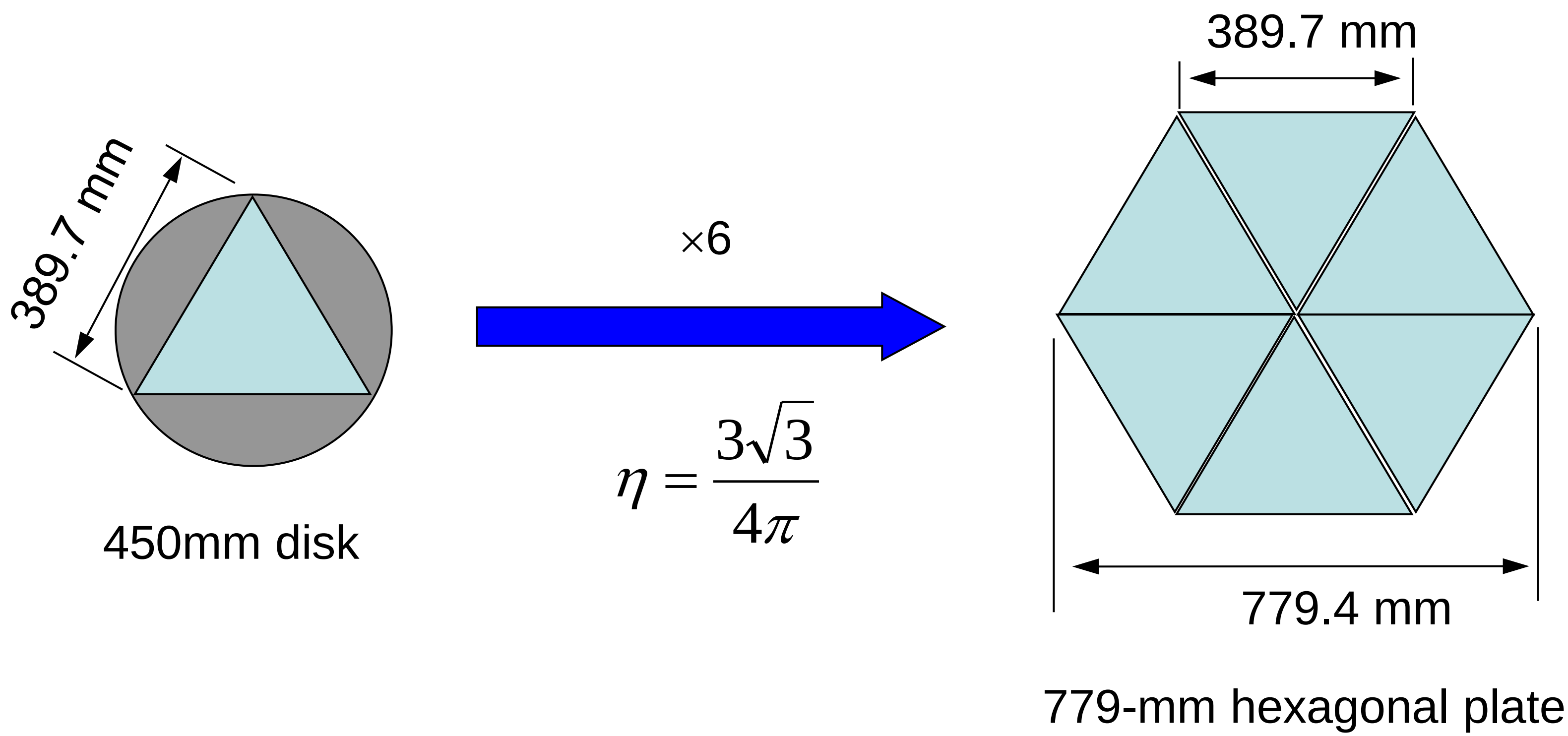
In process to final hexagon

1. **Interface preparation**
2. **Final bond & heat treatment**
3. **Precision surface polish**



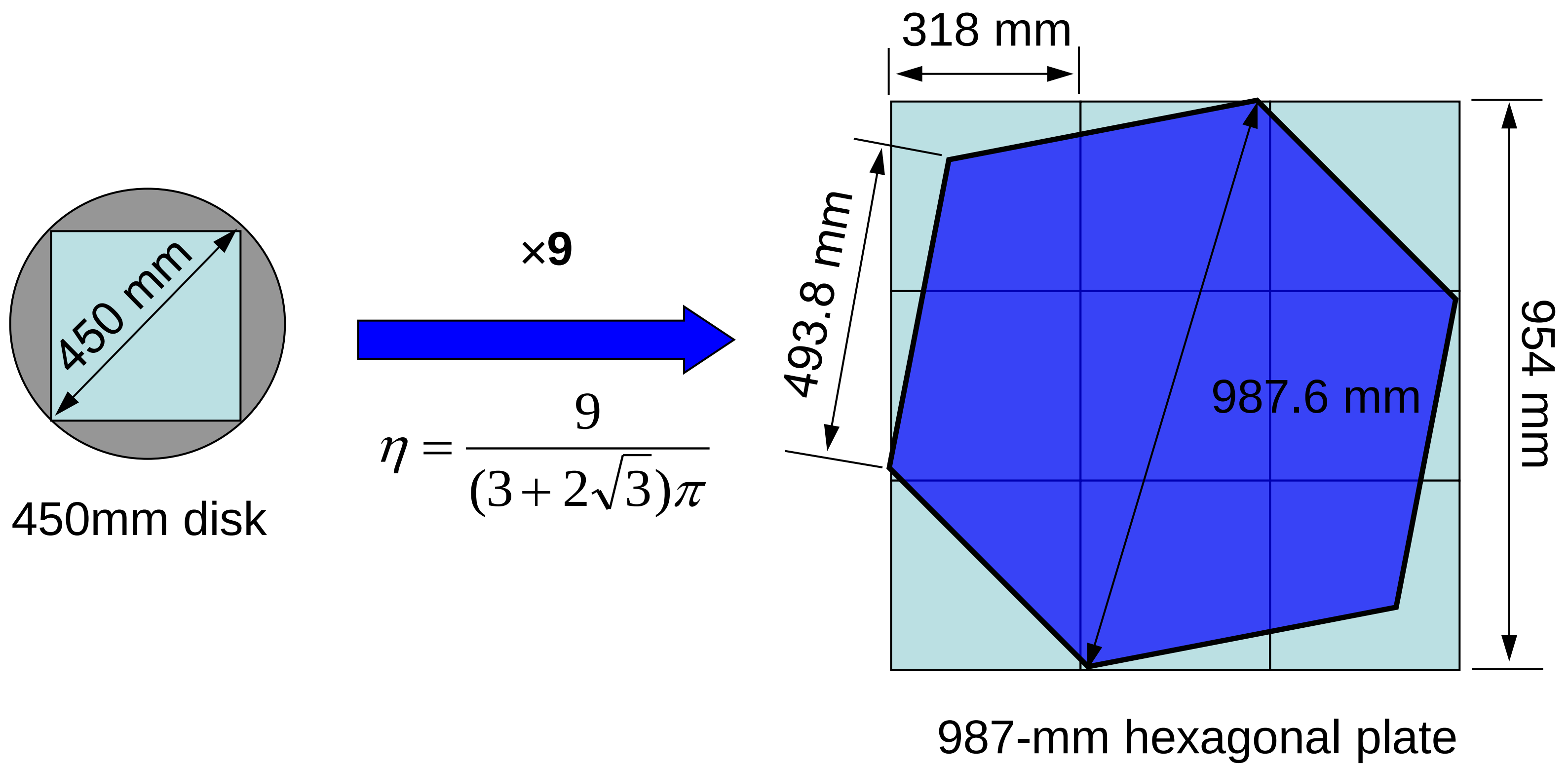
Final hexagonal composite
Estimate: ϕ ~ 12", Thk ~ 2"

Roadmap Toward Meter Level SC-Si Composite (I)



- ***Triangle cut can form near net shape hexagonal composite***
- ***779mm hexagonal SC-Si composite will be formed from 6 wafers***
- ***Final area: 0.395 m^2; Yield: 41.4%***

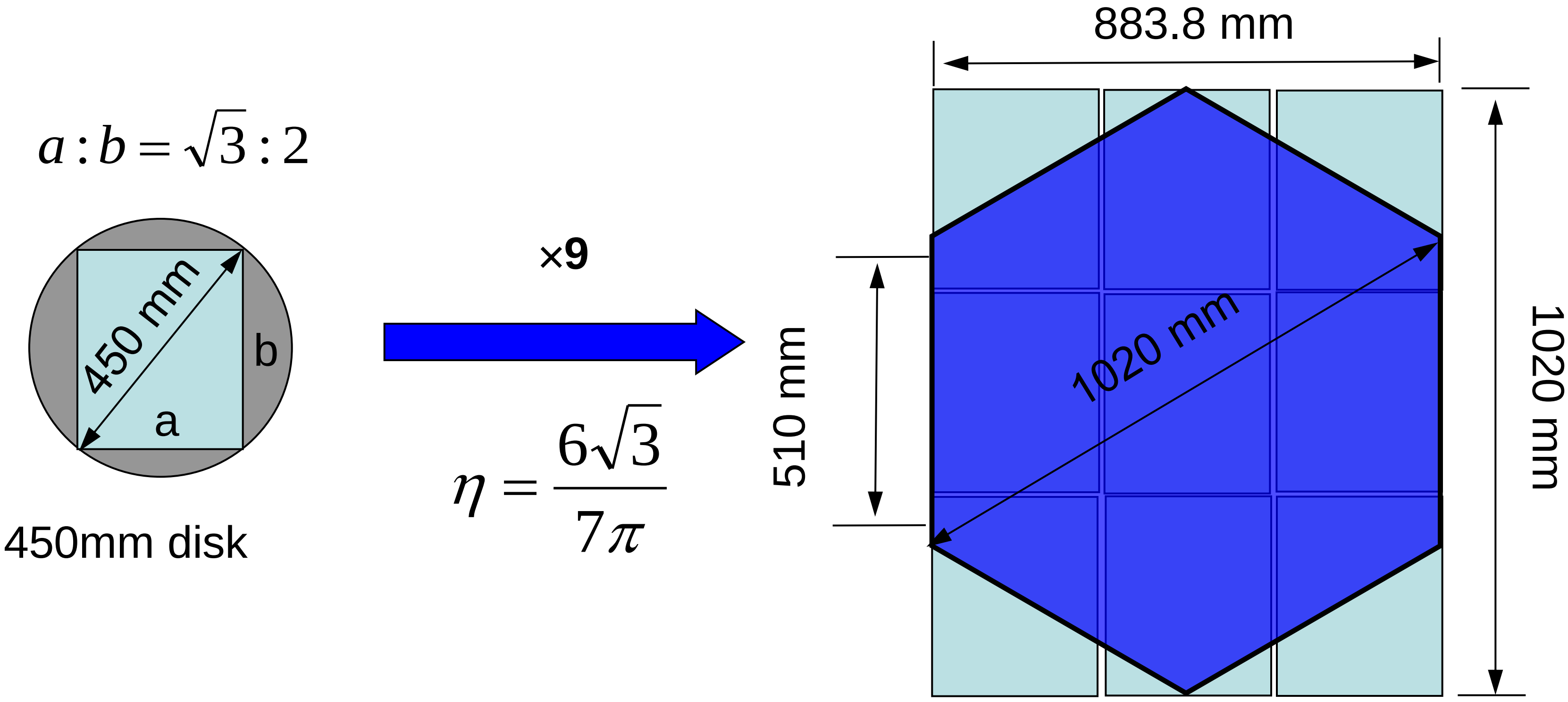
Roadmap Toward Meter Level SC-Si Composite (II)



$$\eta = \frac{9}{(3+2\sqrt{3})\pi}$$

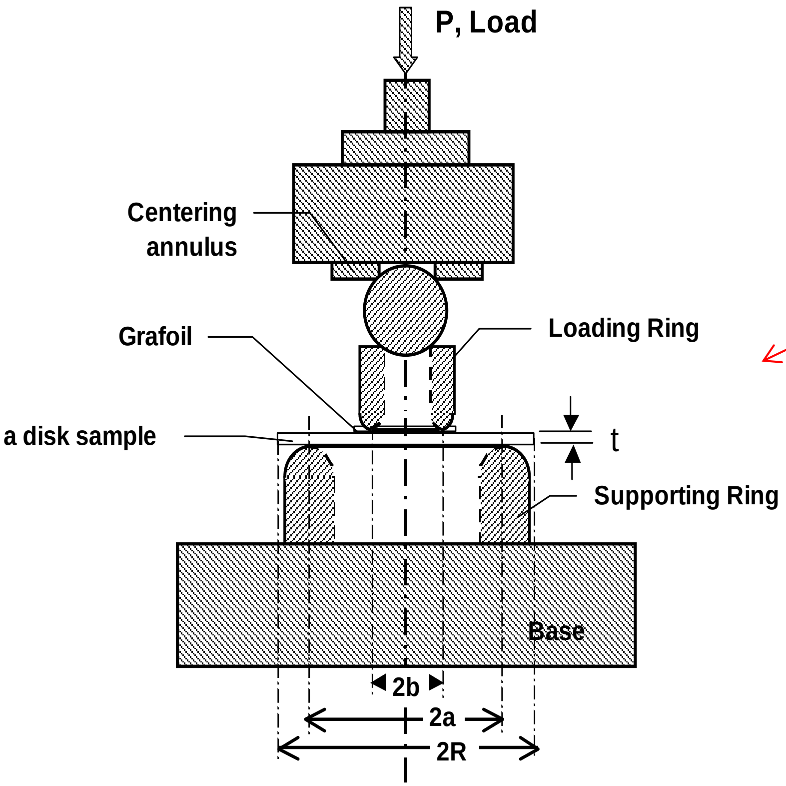
- ***Square cut has the largest available area (63.7%)***
- ***987mm hexagonal SC-Si composite can be formed from 9 wafers***
- ***Final area: 0.634 m^2; Yield: 44.3%***

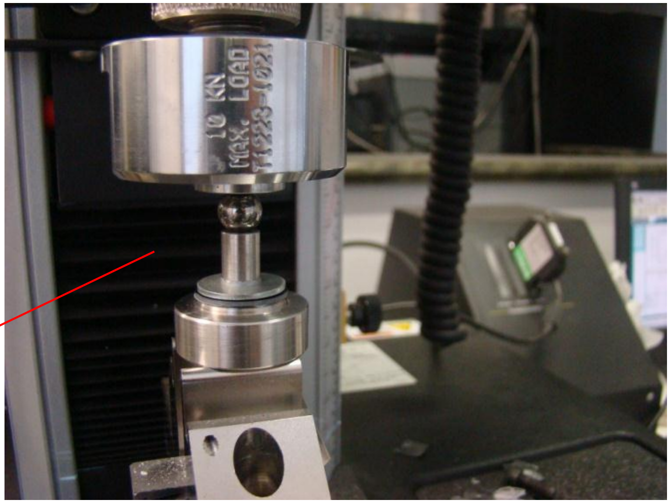
Roadmap Toward Meter Level SC-Si Composite (III)



- ***Rectangular cut at width to length ratio of 0.866 has the highest yield for regular hexagonal composite***
- ***1020mm hexagonal composite can be formed from 9 wafers***
- ***Final area: 0.676 m^2; Yield: 47.3%***

Equi-biaxial flexural strength test



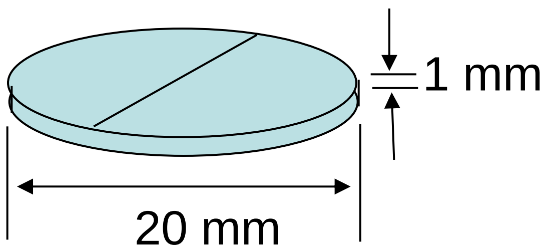


Ring-on-ring test setup

$$\sigma_f = \frac{-3 \cdot P_f}{2 \cdot \pi \cdot t^2} \cdot \left[(1+\upsilon) \cdot \ln\left(\frac{a}{b}\right) + (1-\upsilon) \cdot \left(\frac{a^2 - b^2}{2 \cdot R^2}\right) \right]$$

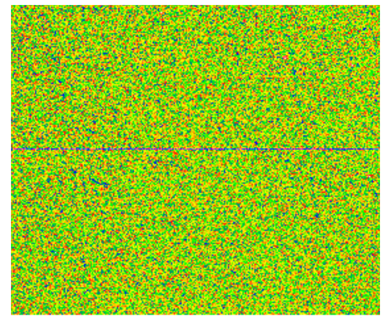
- ***Equi-biaxial flexural strength test according to ASTM C1499-05***

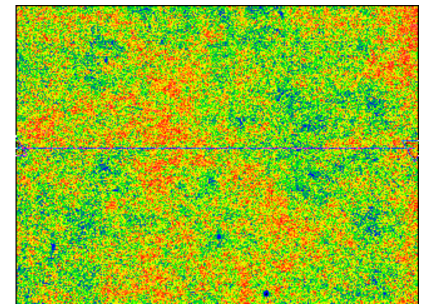
Sample Preparation



Samples for mechanical characterizations

Typical surface finish of test samples


sapphire a-plane, rms = 2.01Å


SC-Si, rms = 0.366 nm

$$\frac{D_s}{10} \geq t \geq \sqrt{2\sigma_f D_s^2 / 3E}$$

$$12 \geq \frac{D - D_s}{t} \geq 2$$

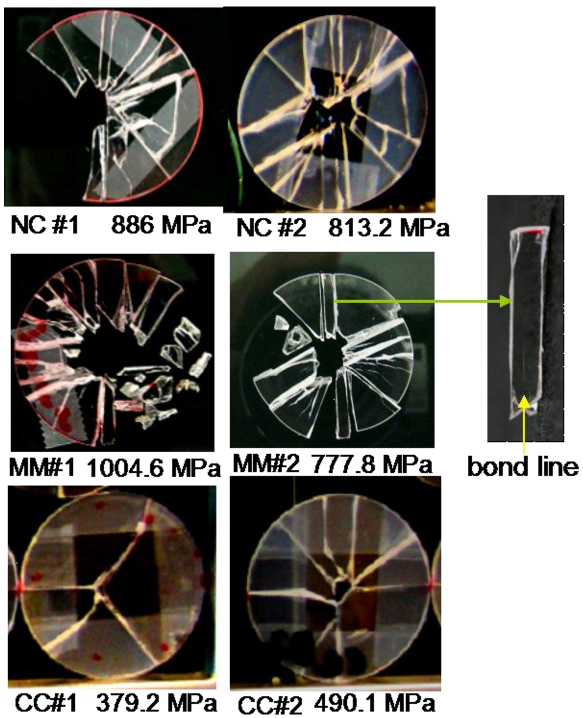
SC-Si
σ_f ~ 300 MPa
E ~ 112 GPa

1.68 mm ≥ *t* ≥ 0.71 mm

28.8 mm ≥ *D* ≥ 18.8 mm

- ***Composite and non-composite samples were prepared for comparisons***
- ***Typical surface roughness < 0.4 nm for SC-Si samples***

Equi-biaxial Flexural Strength of Sapphire Composites

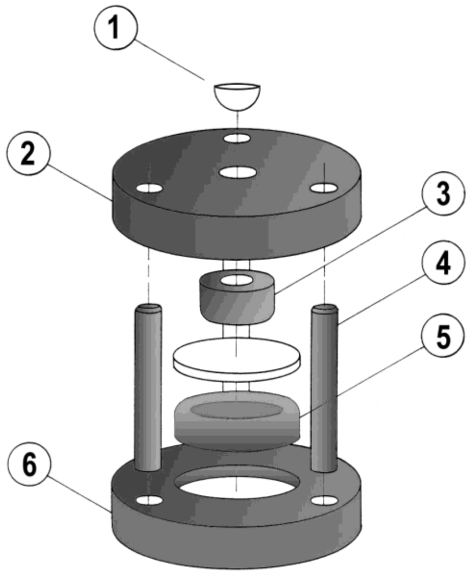


Sapphire Disks	Thickness [mm]	Frac. Load [N]	Fr. Stress [Mpa]	Average [Mpa]
NC#1	1.19	1346.3	886.4	849.8
NC#2	1.19	1235.1	813.2	
MM#1	1.21	1525.8	1004.6	891.2
MM#2	1.2	1181.3	777.8	
CC#1	1.17	707.6	490.1	434.7
CC#2	1.17	547.5	379.2	

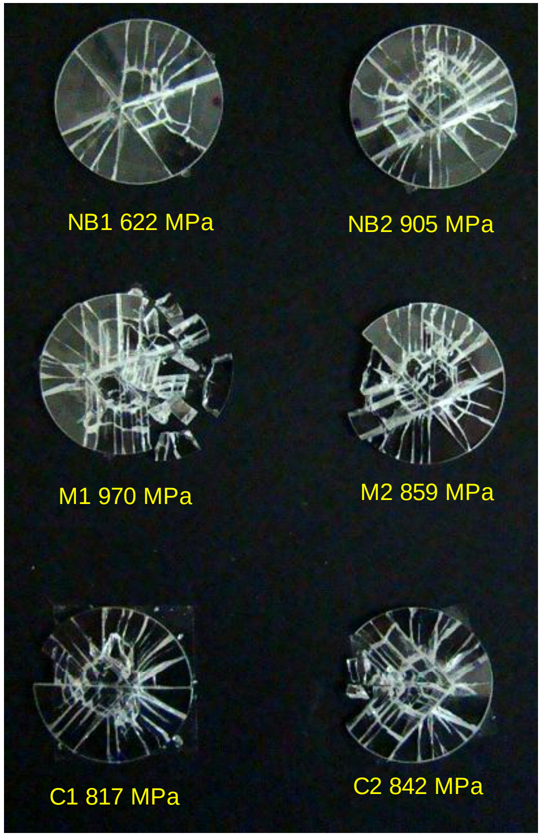
Note: NC = non-composite, MM = m plane bonded, CC= c plane bonded

- ***Observed comparable fracture strength between non-composites and composites***
- ***Lower strength in c-plane bonded sapphire may be explained by lower surface finish***

Equi-biaxial Flexural Strength of Sapphire Composites (UDRI)



1. Load Transfer Bearing
2. Top Support Plate
3. Specimen Load Ring
4. Alignment Post
5. Specimen Support Load Ring
6. Bottom Support Plate



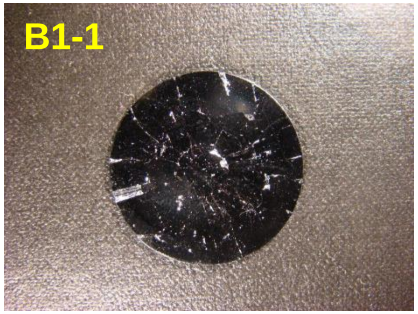
UDRI test results dia. [mm] = 30

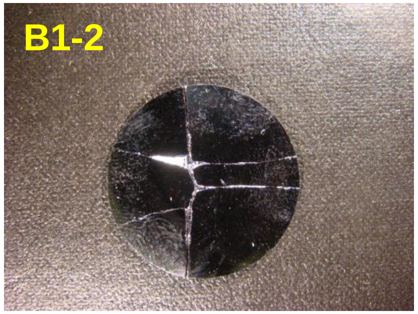
Specimen	Thickness	Load	Equibiaxial Flexure Strength	
Number	(mm)	Newton	(MPa)	
NB1	1.2065	1870.91	622	**763.5**
NB2	1.20396	2709.25	905	
M1	1.20904	2878.53	970	**914.5**
M2	1.20904	2551.12	859	
C1	1.17602	2296.32	817	**829.5**
C2	1.17856	2376.05	842	

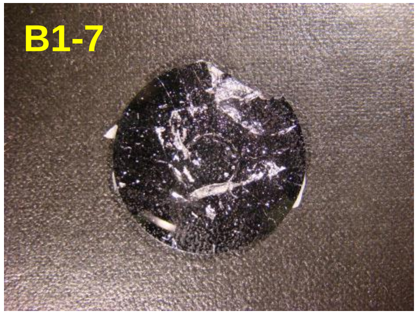
Note: NB = non-composite, m = m plane bonded, c = c plane bonded

UDRI = University of Dayton Research Institute

Equi-biaxial Flexural Strength of SC-Si





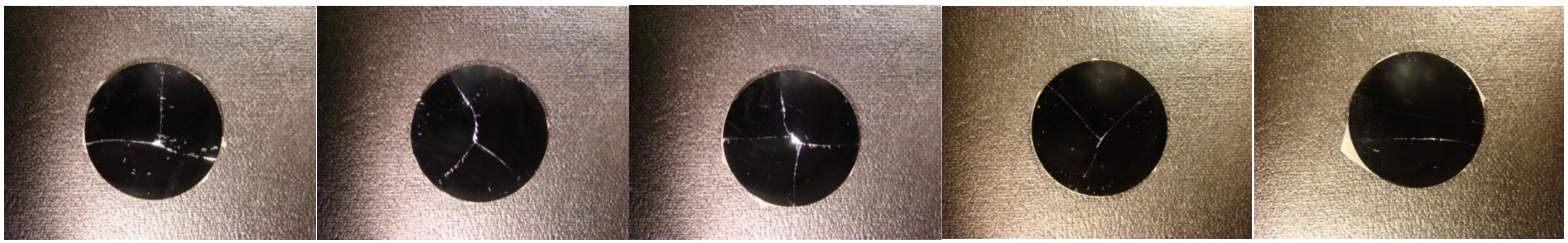


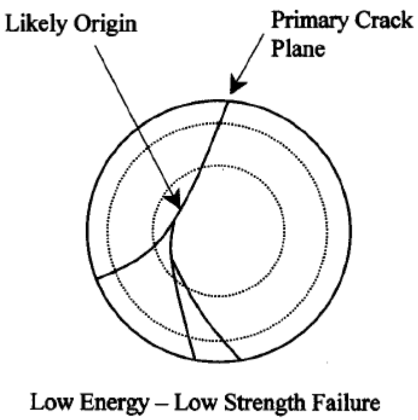
No.	D (mm)	t (mm)	Frac. Load (N)		σ_f (MPa)
B1-1	23	1.007	564.11		373.95
B1-2	23	1.003	205.28		137.17
B1-3	23	1.008	695.1		459.87
B1-4	23	1.009	691.88		456.83
B1-6	23	1.007	546.76		362.45
B1-7	23	1.008	831.9		550.37

Average: 390±141 MPa

- ***Surface scratches cause significantly lower flexural strength in Sample B1-2***

Equi-biaxial Flexural Strength of Composite SC-Si





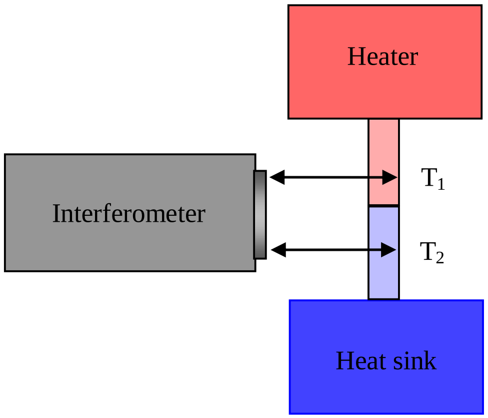
ASTM C1499-08

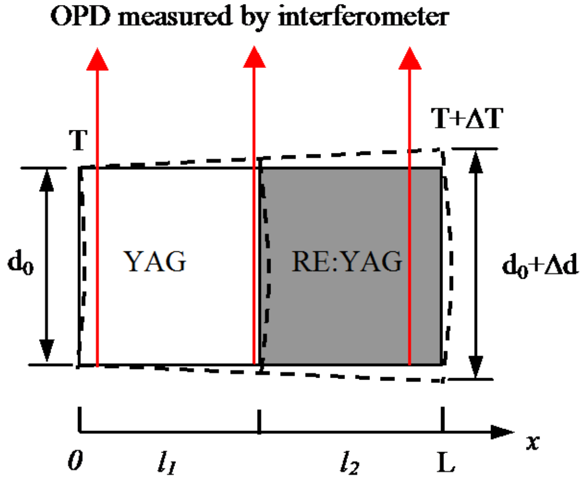
No.	D (mm)	t (mm)	Frac. Load (N)		σ_f (MPa)
E2-A	20.03	1.019	45.04		30.24
E2-B	20.03	1.015	74.26		50.26
E2-C	19.98	1.017	42.21		28.48
E2-D	20.03	1.017	80.76		54.44
E2-E	20.03	1.017	87.46		58.96

Average: 44.5±14 MPa

- ***No breakage at bonding interface***
- ***Low flexural strength could be due to micron cracks or heat treatment history.***
- ***More experiments will be performed to pinpoint the reason***

Interferometric thermal measurement





- ***Optical path length is temperature related***

$$\Delta OPL(x) \approx d_0 (n_0 \cdot \alpha + \frac{dn}{dT}) \Delta T(x)$$

$\gamma = n_0 \cdot \alpha + dn/dT$

— ***Thermal coefficient of expansion of optical path length***

— ***Can be measured or calculated***

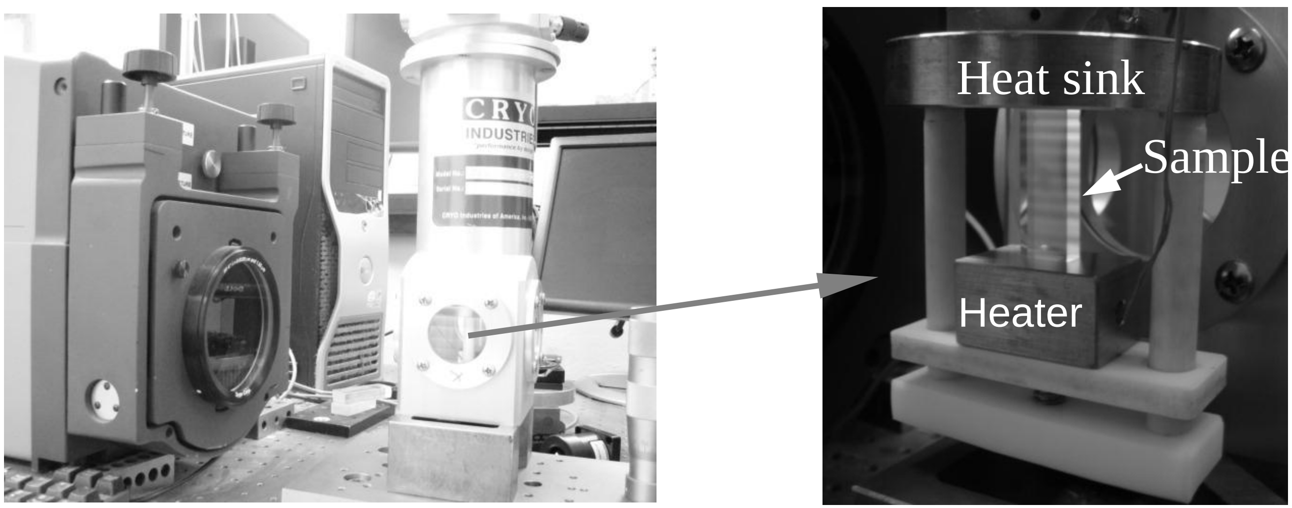
- ***Steady-state temperature distribution:***

$$\begin{cases} \Delta T(x) = \dfrac{Q \cdot x}{K_1 \cdot S} & for \quad x < l_1 \\ \Delta T(x) = \dfrac{Q \cdot l_1}{K_1 \cdot S} + \dfrac{Q}{H \cdot S} + \dfrac{Q \cdot x}{K_2 \cdot S} & for \quad x > l_1 \end{cases}$$

— ***K1, K2, thermal conductivities of YAG and rare-earth doped YAG***

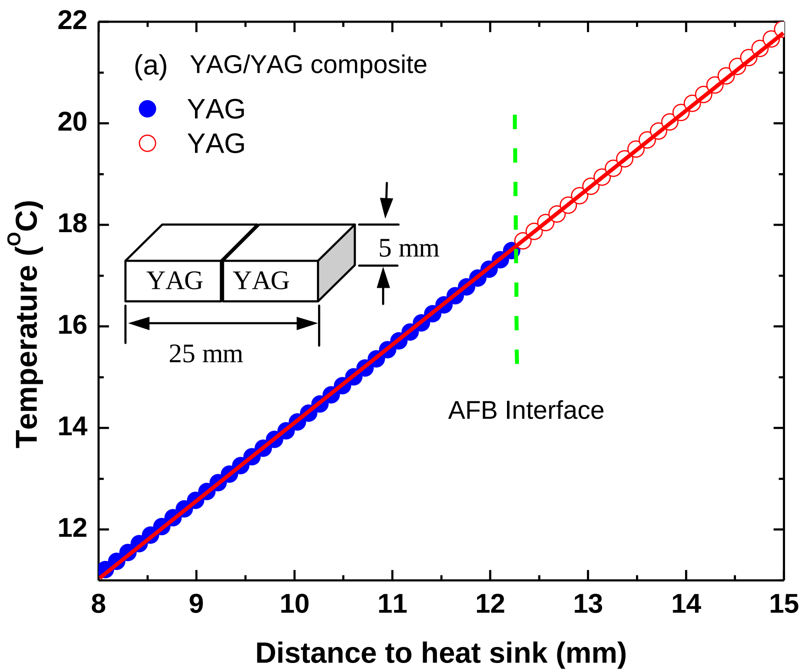
— ***H, heat transfer coefficient of AFB interface***

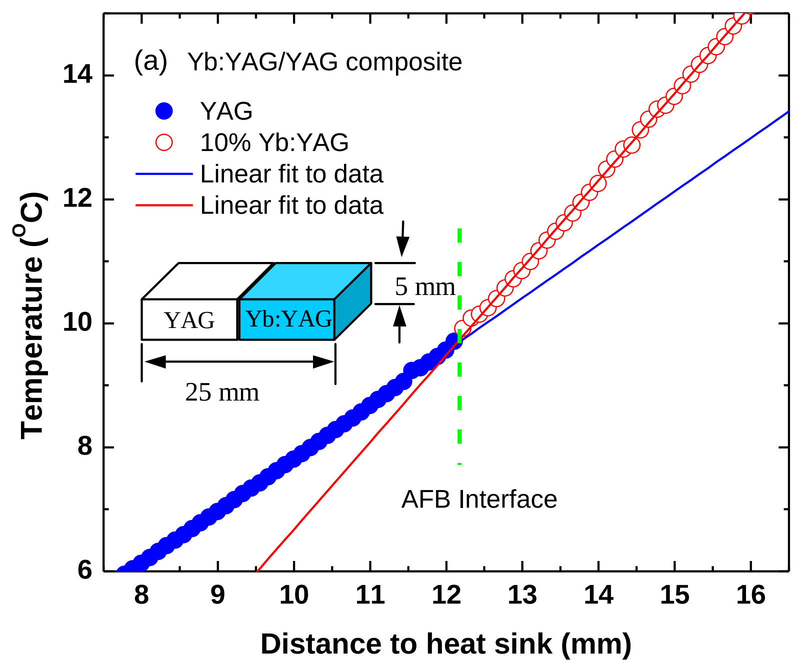
Setup for interferometric thermal measurement



- ***Mounted in vacuum cryostat to prevent heat convection loss***
- ***Cryogenic temperature distributions can be measured***
- ***Zygo phase-shifting interferometer: Accuracy for OPD <1/1000 of λ***
- ***Accuracy of ΔT : <0.02 ℃ in 5-mm wide YAG crystal***

Thermal Test results of YAG composites





- ***Non-measurable temperature interruption at AFB® bonding interface***
  - ***— Negligible heat transfer resistances***
- ***Different temperature gradients in YAG and Yb:YAG***
  - ***— K=9.06 W/m•℃ for 10% Yb:YAG vs. 13 W/m•℃ for YAG***
- ***Thermal measurements in Si composites are in process***

Summary

- ***Two 12” wide trapezoids each edge-bonded from 3 equilateral triangles have been demonstrated. One more bond needed to form a final 12” hexagon***

- ***Technique roadmap toward meter level SC-Si composite has been discussed***

- ***Demonstrated excellent thermal and mechanical properties of AFB® bond in Sapphire and YAG composite. Experiments in SC-Si composites are in process***