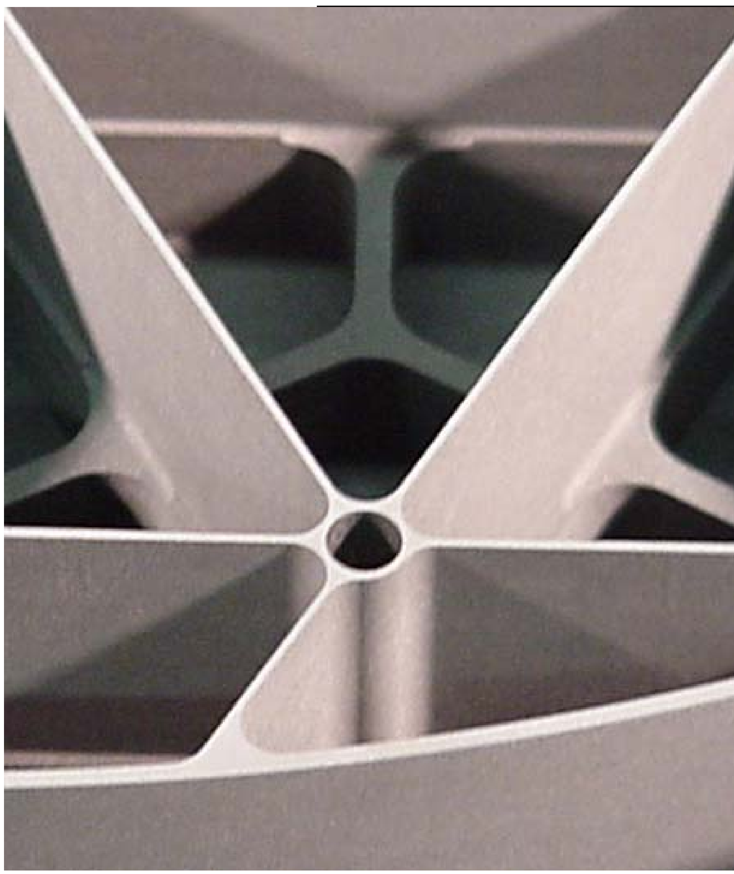
A Low-Cost Innovative Approach for the Fabrication of Net-Shape SiC Components for Mirror Substrate Applications



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Acknowledgements

- **Phase I SBIR**
- **This work was done under contract** F29601-03-M-0287 (MDA 03-048) through AFRL- Space Vehicles Directorate, Kirtland AFB, NM.
- Dr. Arup Maji was the technical monitor.

Presentation Outline

- Overview of Silicon Carbide for mirrors
- POCO process for SiC substrates
- Innovative Research Issues
- Results and Conclusions
- Future Work
- Summary

Property Requirements for Materials in Optics

Low	High	Benefit
Density (ρ)	Elastic Modulus (E)	High Specific Stiffness (E/ρ)
CTE (α)	Thermal Conductivity (κ)	High Stability Factor (κ/α)
	Thermal Diffusivity (D) & Heat Capacity (C)	High Thermal Conductivity
Poisson's Ratio	Strength & Fracture Toughness	Long-Term Stability

Beryllium has been a material of choice, particularly for cryogenic applications

Opportunity

- There is a need for a new materials high performance optics applications.
- There is a desire to replace Beryllium in many applications due to:
  - Cost
  - Schedule
  - Health concerns

Criteria for Material Selection

- Property requirements compared to beryllium
  - high specific stiffness
  - high thermal stability
  - high thermal conductivity
  - long term stability
- Manufacturability of complex shapes.
- Cost and Schedule.

Material Properties Comparison

Material	Density (ρ)	Elastic modulus (E)	Thermal expansion (α)	Thermal conductivity (κ)	Specific Stiffness (E/ρ)	Thermal Stability Parameter (κ/α)
Units	g/cm^3	GPa	$x\ 10^{-6}/K$	W/m-K	kN-m/g	W/μm
RB SiC	2.92	310	2.4	157	106	65
CVD SiC	3.21	466	2.2	300	145	136
HP SiC	3.20	455	2.6	155	142	60
Sintered SiC	3.16	415	2.5	114	131	46
Beryllium	1.85	303	11.4	216	164	20
Zerodur ® [7]	2.53	91	0.05	1.64	36	33
BK7 (glass)	2.53	81	7.1	1.12	32	0.16
SXA	2.91	117	13.0	125	40	9.62
Aluminum	2.7	68	23.6	170	25	7.20
POCO SiC	2.53	218	2.4	153	85	64

Advantages of Silicon Carbide

- **Very high thermal conductivity combined with very low thermal expansion. Higher thermal stability (κ/α) than most materials listed**
- **Higher specific stiffness than all materials listed except Be due to primarily its lower density**
- **Reasonable thermal expansion (much lower than that of Be)**
- **Remarkable long-term dimensional stability even under the influence of extreme environmental conditions**
- **Conclusion: SiC is the Material of Choice to Replace Be**

POCO SiC Manufacturing Process

POCO Proprietary Graphite

Tolerance ±0.001”

Machining

Purification

Assembly (if needed)

Tolerance ±0.003”

Convert Graphite Completely to beta SiC

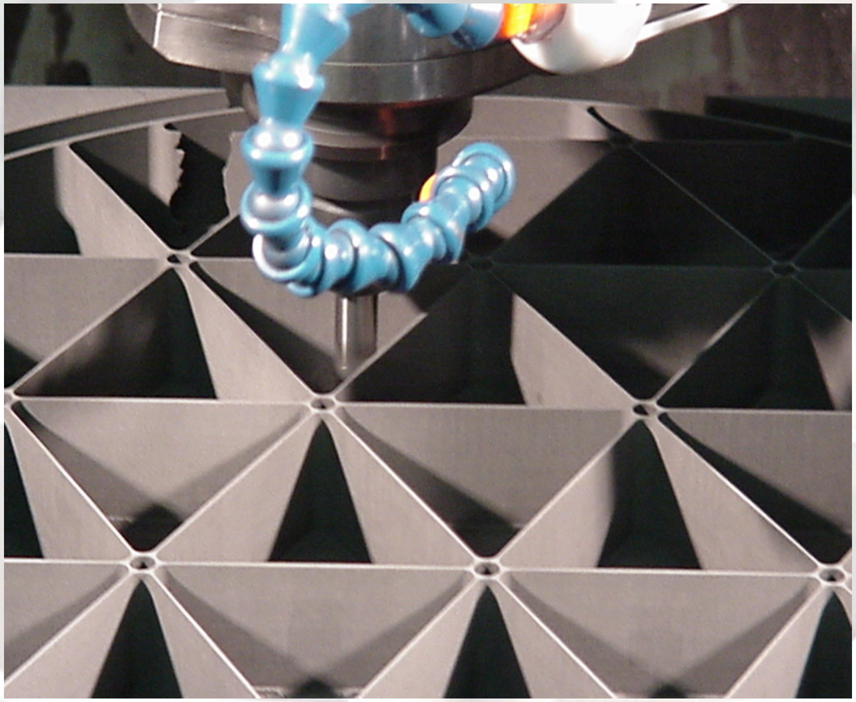
Rough Figure Machining

0.008” thick

Coat Finished Part with CVD SiC

Final Figuring & Polish Precision Optical Surfaces

Graphite Design & Machining



Machining Open Back Graphite Substrate

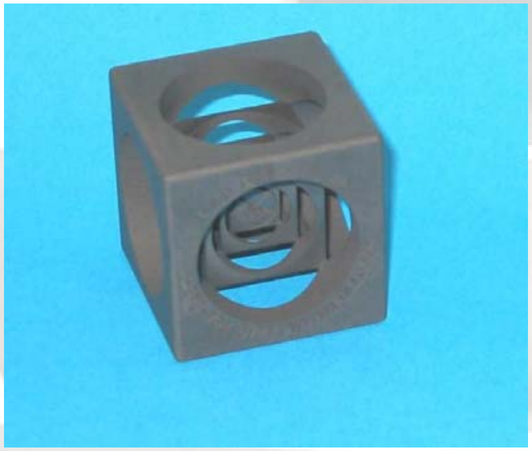
- **Advantages**
  - Wall thickness
  - Strength
  - Reproducibility
  - Design flexibility

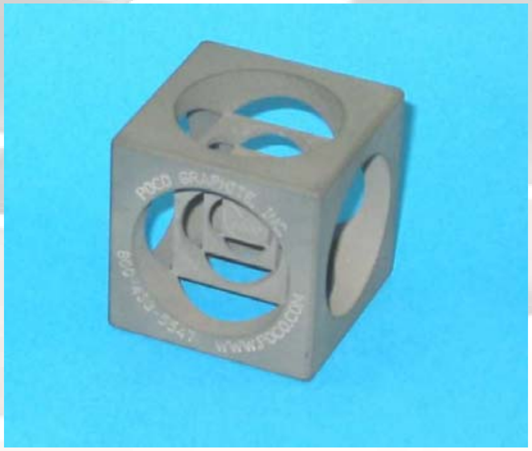
  - Graphite Availability
    - Petroleum Coke
      - Millions of Tons
    - Graphite Thousands of Tons

The Chemical Vapor Conversion (CVC) Reaction

Purified, Machined, net-shape Graphite

Polycrystalline, Stoichiometric ß-SiC





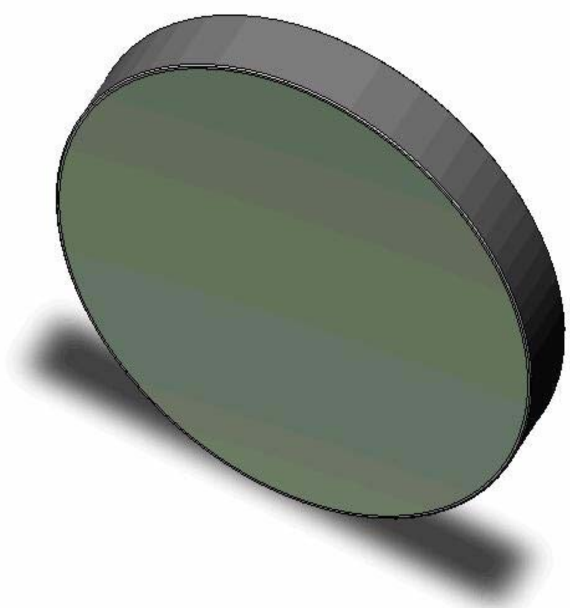
$$2C + SiO \rightarrow SiC + CO$$

No sintering aid or bond phase

Advantages of POCO SiC

- Manufacturing process
  - Near net-shape – Consistent dimensional changes as a result of C $\Rightarrow$ SiC conversion and CTE change
  - High shape complexity due to ease of graphite machining – Comparable to Aluminum
  - Low cost due to absence of tooling charges and post machining
  - Short lead time due to the unique nature of the process
  - Graphite engineered for conversion to SiC
  - POCO practices Continuous Improvement
  - Quality control is part of POCO culture.
- Silicon Carbide Product
  - High purity due to absence of any additives
  - SiC properties controlled by starting graphite properties

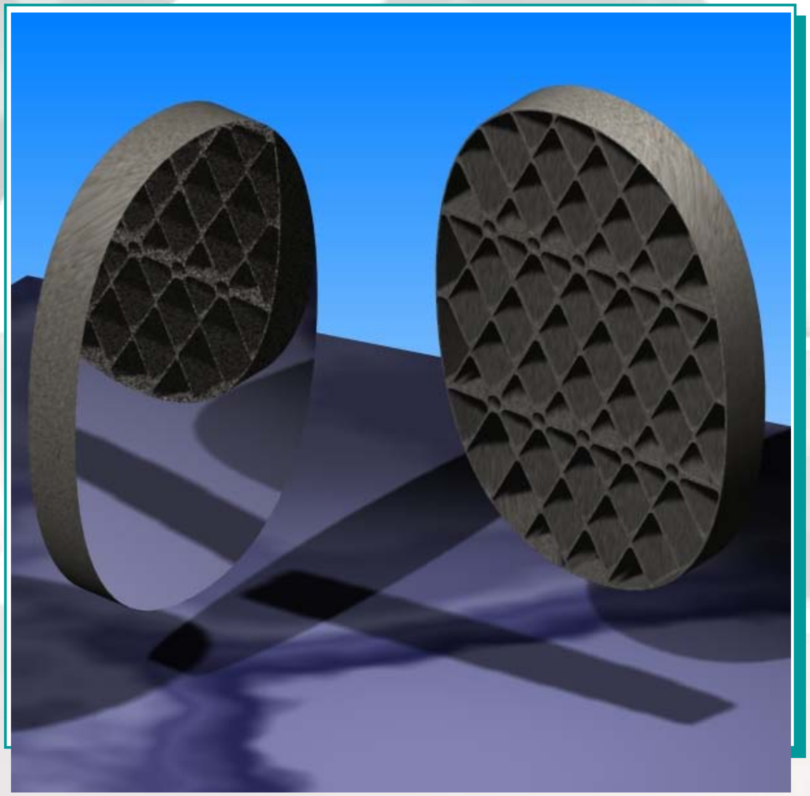
POCO SuperSiC™ Mirror Delivered to MSFC



- Circular periphery 0.25 meter diameter (9.75 inches)
- 50-100 mm(1-2 inch) depth
- Radius of curvature of 3 meters. (118 inches)
- This mirror has a lightweighting structure
- Polished to optical figure error of less than 0.25 wave RMS
- Surface roughness of approximately 10 angstroms RMS.
- No distortion of Figure down to 23°K

Characteristics of Typical SuperSiC Mirror

Recently Manufactured SiC Mirror



Performance Benefits

- **Greatly Improved Visible & SWIR EOD / Sensitivity**
- **Improved Closely Spaced Object Resolution**
  (Sunlit Targets)

Performance Achieved

Mass: 0.993 Kg
Areal Density: 18.7 Kg/sq m
Periphery: 0.200 x 0.300 meter
Thickness: .045 meter
Optical Surface: Flat, surface roughness = 3.2 Å
Optical figure: 0.26 wave (0.6328 microns)
Cryo Test: *mirror showed no significant change in the magnitude of the RMS wavefront error (WFE) over a temperature range from 110 K to 380 K*.

Technical Objective and Approach

- The overall objective of this program was to develop a post process for the densification of near-net shape 15%-porous SuperSiC preforms by converting the available porosity in the SiC part to a new SiC phase.
- A two-step approach to achieve this objective:
  - ◆ Produce a carbon structure with open interconnected microposository within the original pores of the SiC preform. Multiple PIP cycles using a liquid carbon precursor mixed with a suitable pore-forming agent is used to produce the porous glassy carbon.
  - ◆ Convert the above carbon structure to SiC using silicon (reactive melt infiltration process). The produced new phase of SiC is known as the reaction-formed SiC (RFSC).

Description of the Process

- Produce near net-shape porous SuperSiC™ part using POCO's conversion process
- Impregnate the porous SuperSiC™ part with the carbon precursor
  - Cure
  - Pyrolyze
- The result is a carbon structure with interconnected microscopic porosity residing in the open pores of the part to be densified.
- Infiltrate with silicon to convert carbon to SiC
  The final result is a new reaction-formed SiC (RFSC), with very little or no free silicon, filling the open porosity of the SuperSiC part
- Apply CVD SiC coating, if needed

Properties of Densified SuperSiC

Property	Desired Value	Be	CVD SiC	RB SiC	HP SiC	Sintered SiC	SiC-1 Preform	RFSC Densified SiC
Density (g/cm^3)	Low	1.85	3.21	2.92	3.20	3.16	2.53	**3.05**
Young's Modulus (GPa)	High	303	466	310	451	415	218	**337**
Specific Stiffness (kN·m/g)	High	164	145	106	141	131	85	**110**
Knoop Hardness (kg/mm^2)			2540				2000	**1900**
CTE (ppm/°C)	Low	11.4	2.2	2.4	2.6	2.5	2.4	**Not measured**
Thermal Diffusivity (mm^2/s)	High	64	146	80	75	51	92	**109**
Heat Capacity (J/kg·K)	High	1820	640	670	550	715	660	**Not measured**
Thermal Conductivity (W/m·K)	High	216	300	157	155	114	157	**218**
Thermal Distortion (µm/W)	Low	0.053	0.007	0.015	0.017	0.022	0.015	**0.011**

Further Development

- Test the process for repeatability and uniformity.
- Demonstrate the process for the densification of complex shapes such as small mirror substrates.
- Demonstrate the CVD SiC coating of densified plates and their polishability.

Summary

- Silicon carbide is the material of choice to replace Be
- POCO's process has the advantage of manufacturing capability to produce very complex shape SiC products at lower cost
- POCO has the advantage of producing own graphite for conversion to SiC ensuring a continuous quality control
- POCO's SuperSiC™ material has good mechanical and thermal properties needed for optics and other applications
- There is still room for improvement via the densification of POCO's SuperSiC™ using the proposed approach
- Preliminary results showed a significant increase in flexural strength and stiffness for the densified SiC material
- SOME applications may require a denser material