McCARTER

Single Crystal Silicon Mirrors

Our Unique Manufacturing Approach

August 17, 2005

McCARTER

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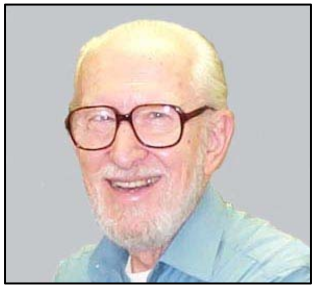


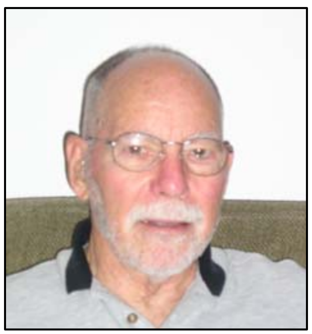
Frank Anthony
Analytical Scientist
St.Patricks Day 2003

In memory of and appreciation for quantifying our successful machining methods, teaching us to frit bond, authoring our 5 technical papers and donating his 45 years of his library collection to McCarter.

A graduate of MIT, Anthony had 46 years of thermal structural experience. He worked at Boeing for 6 years as a consultant, and Bell Aerospace for 35 years a Program Manager and Technical Director for silicon laser mirror and developmental contracts.

Welcome to Dr. Roger Paquin

Advanced Materials Consultant



Dr. Roger Paquin

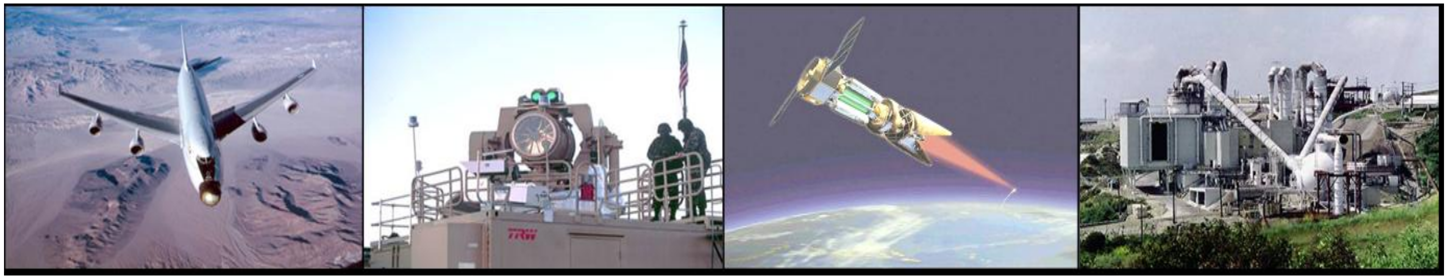
A graduate of Stevens Institute of Technology, Dr. Paquin is a Fellow of SPIE and IOES, as well as a member of ASM International.

Dr. Paquin is world renowned Material Scientist who has developed processes and procedures that enabled the manufacturing of Mirrors and Telescopes that are currently in use and production.

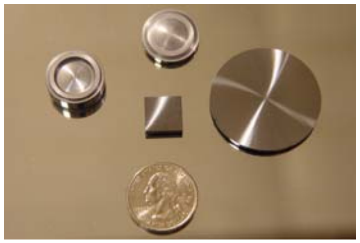
At McCarter, Dr. Paquin will review, guide and assist our effort to implement single crystal Silicon, in place of Beryllium. He will also be our consultant in the High Energy Laser SCSi Mirrors and High Performance Cooled SCSi Mirror Programs

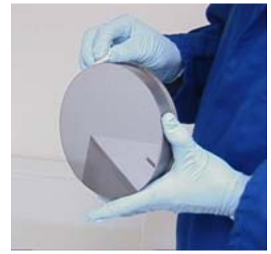
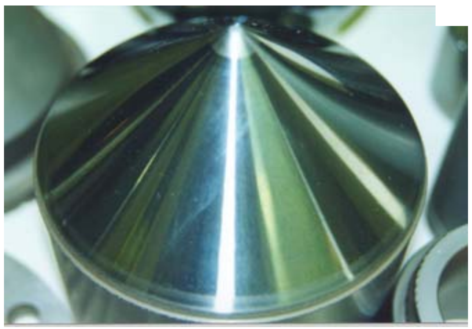
SCSi Optic Customers since1993

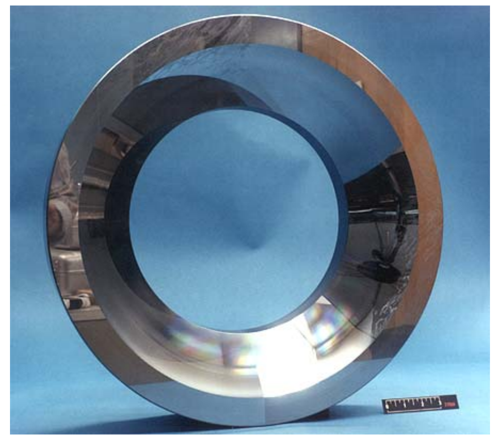
- **Northrop Grumman Space Technology**
- **Raytheon Missile Systems**
- **Raytheon Elcan**
- **Goddard Space Flight Center**
- **Argonne National Lab**



SCSi Mirrors Manufactured by McCarter





Small (.20”)

Tertiary

Simplistic Lightweight

Conical

Cooled

Annular (60.00”)

Advanced Lightweight

Synchrotron

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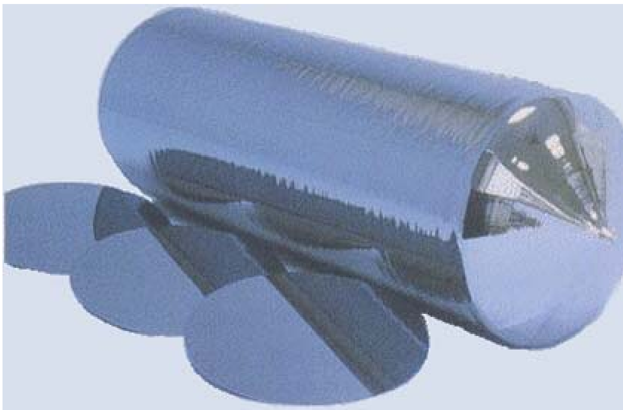
Manufacturing Processes



- Zero-D Material Procurement
- Rapid Removal Equipment and Customized Tooling
- Cuts Manufacturing Time from 21 days to 3 days
- Proven and Repeatable

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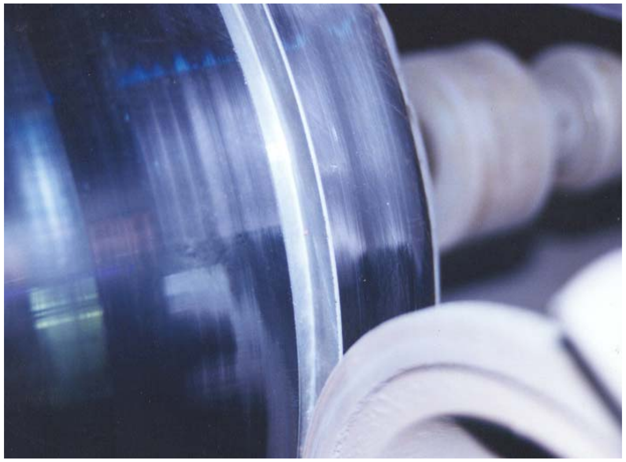
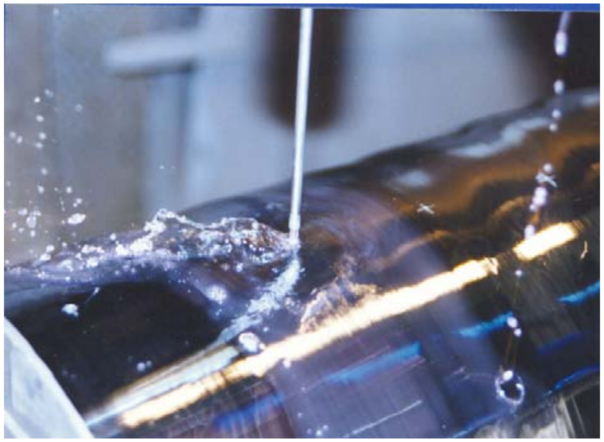
Machining Processes

Slicing

Turning



Grooving



Drilling

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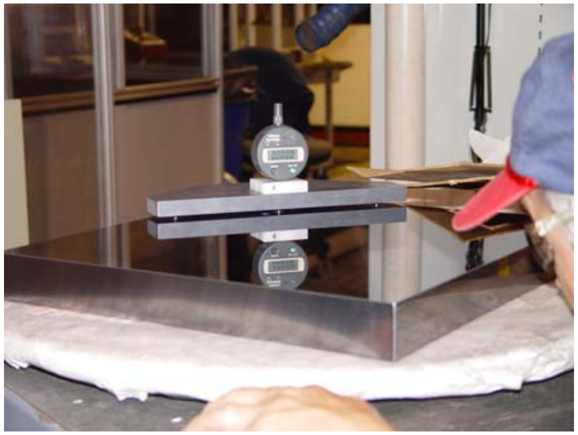
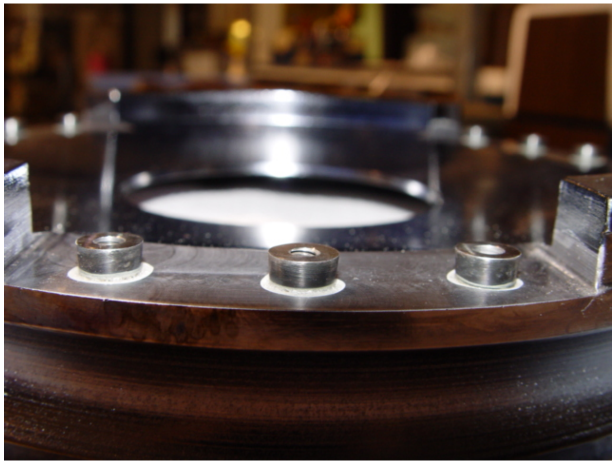
Proprietary and/or Patented Processes



Superfinished and Frit bonded

Etching and Cleaning

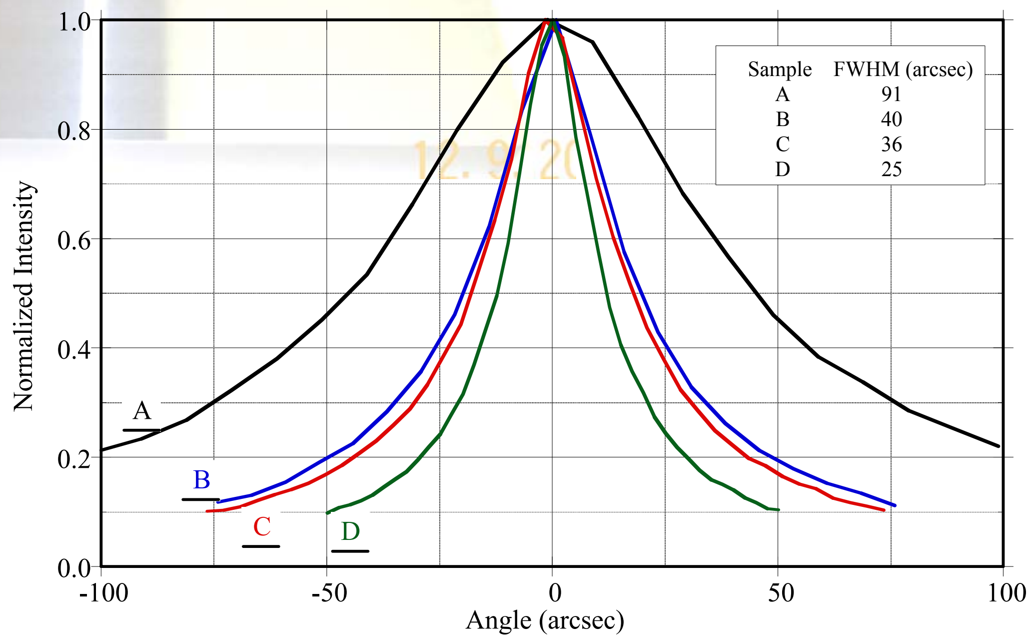
Frit Bonding Preparation



Metal Inserts in SCSi

Test Results –

SSD Removed by McCarter Superfinish

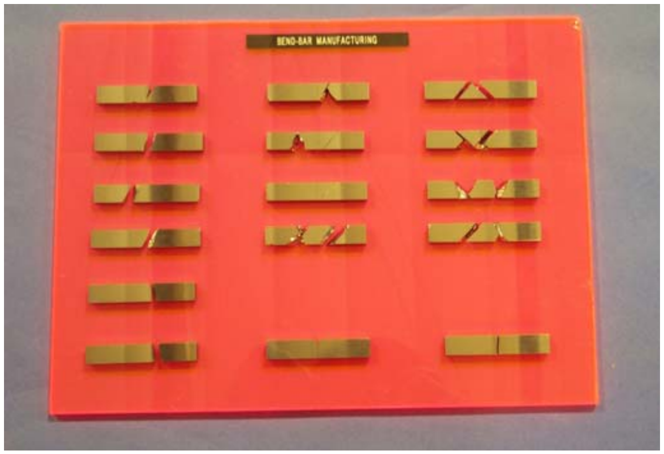


Normalized rocking curves of the four samples. The insert shows their Full Width Half Height values. A – 400 grit B – 600 grit C – 800 grit D – McCarter Superfinish

Awarded US Patent 6,443,817 for Superfinish Process

Test Results –
Frit Bonding Allows Complexity

Strength Test Results



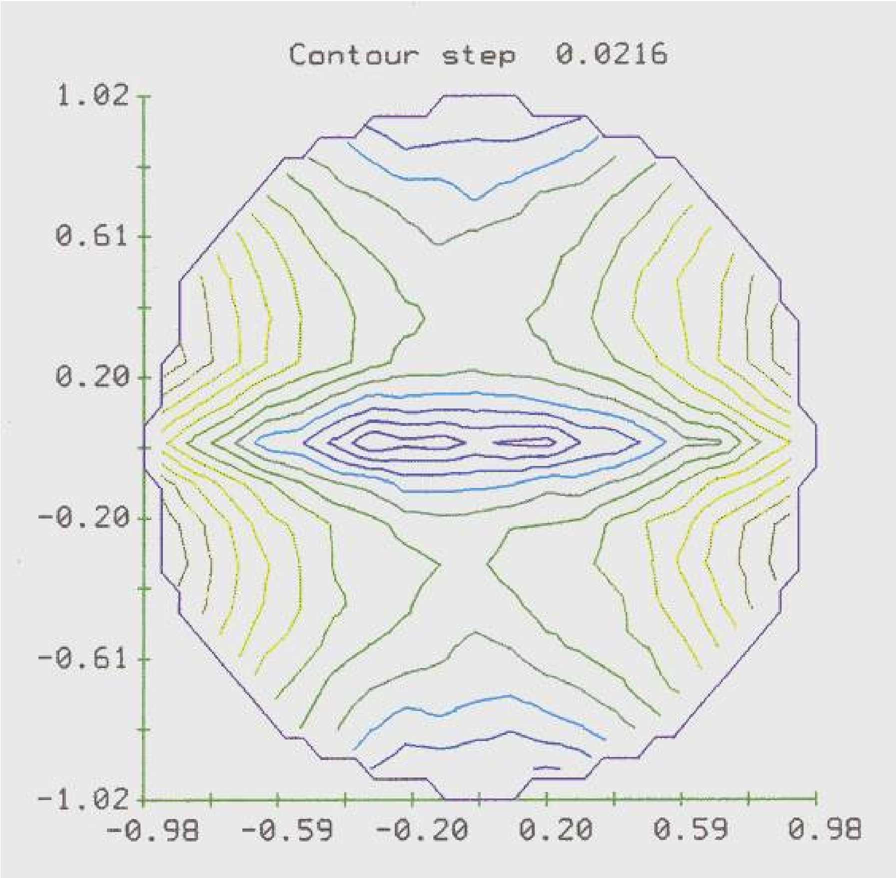
Silicon Frit Bonded Bend Bars

- **4-Point bend strength measured of three types of bars per MIL_STD 1942**
  - **Silicon (not shown)**
  - **Bonded Silicon**
  - **Cryocycled Bonded Samples (not shown)**

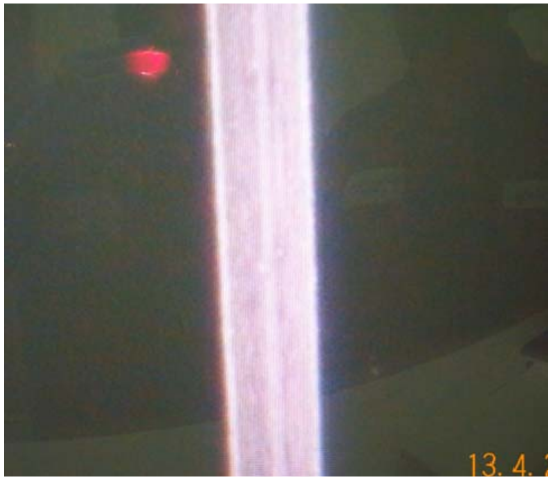
Type of Bar	Number	Average Strength (psi)	Standard Deviation (psi)	Standard Deviation Average (psi)
Silicon	5	14711	2891	0.1965
Bonded Silicon	10	13350	3086	0.2312
Cryocycled	7	12480	2423	0.1942
Bonded Silicon	8	16092	3136	0.1949

4-Point Bend Strength Test Performed at Alfred University

Test Result –
Optical Polishing over Frit Bond Joint



Polished to λ/17rms



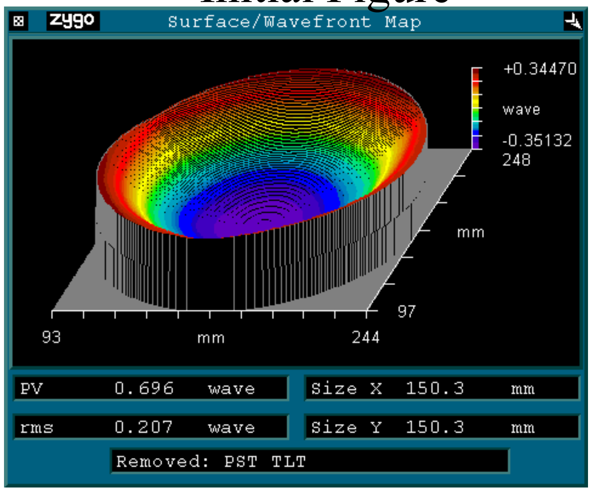
No Discontinuity

3-plank polished plate

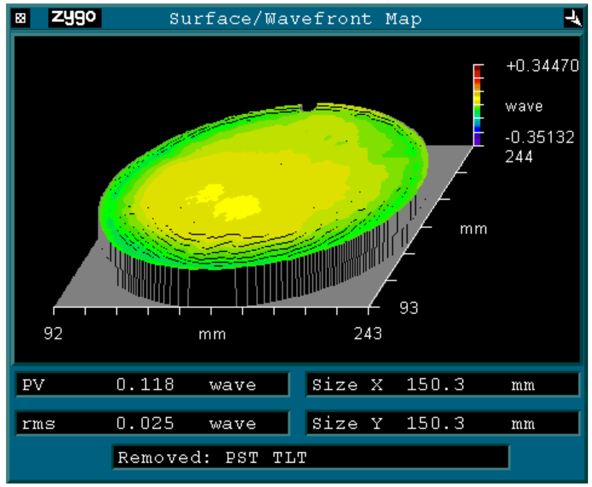
Test Result –

Light-Weight SCSi Mirror Print through Removal

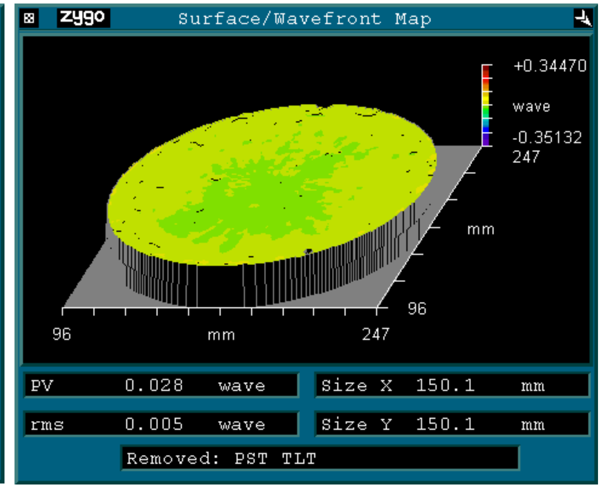
Initial Figure



After 1 iteration

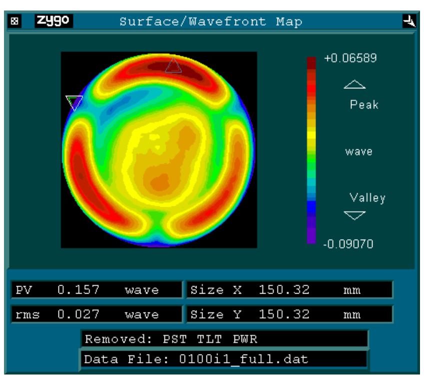


After 2 iterations

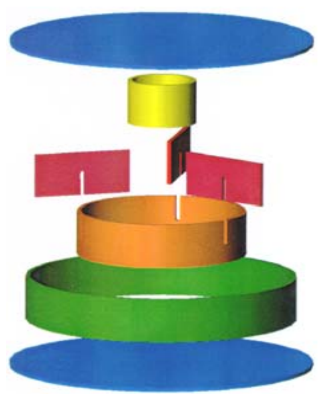


67 minutes

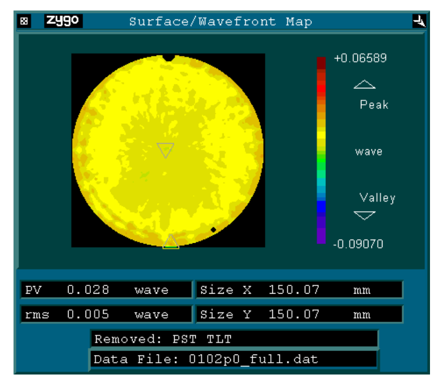
10 minutes



Initial figure (with "power" removed) shows "print through" of support structure.



Schematic showing the general structure of the McCarter Single Crystal Frit-Bonded Silicon Lightweight Mirror



Final figure shows no "print through" of support structure.

Test Result –
Insert Process Adds Modularity

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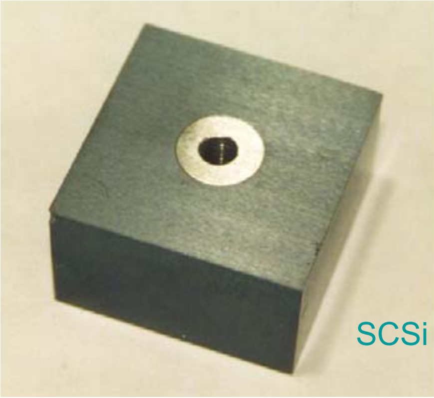
Fatigue Test



Sequence	Name	Description	Location on Tape	Failure Point lbs
1	GK-2	Si-39Ni	0:00:11	771
2	GK-3	Si-39Ni	0:01:06	551
3	SiC	SiC-39Ni	0:01:40	1239
4	GJ-3	Si-39Ni	0:03:40	281
5	GJ-2	Si-39Ni	0:04:40	Bolt Bent
6	GJ-2	Si-39Ni	0:07:00	1220
7	Tangent Flange	SiC-39Ni	0:07:25	1042

All strengths are verified by McCarter video tape.

- Silicon tends to fail before the frit-bonded joint fails.
- The initial quality control in selecting zero-d material is critical.
- In addition all subsequent processing operations can either enhance or defect the material strength.

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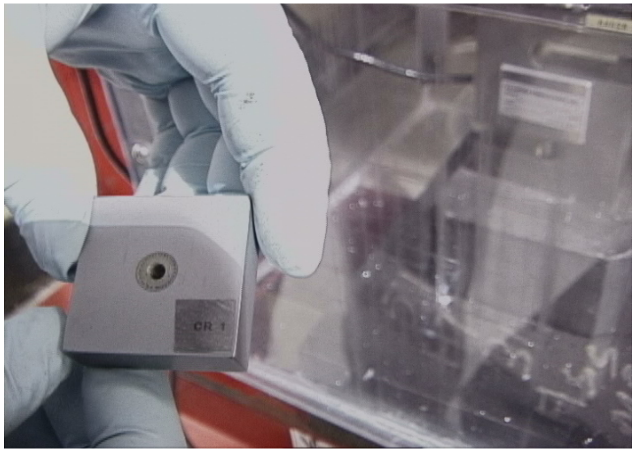
Insert Process

Fatigue Testing after Cryo

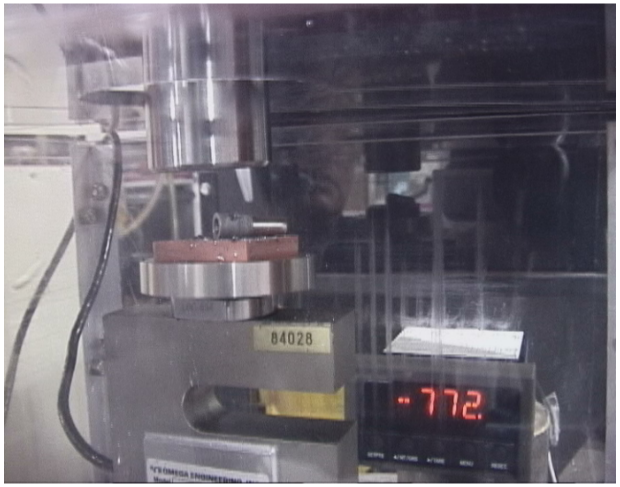
Confirmed by Video



SCSi Block w/ 39NiFe Insert

Before Cryo 398lb/sq in

Post Rupture Reveals Excellent
Frit Adhesion to Insert



After Cryo 772lb/sq in

Cryostability of Lightweighted SCSi Mirror

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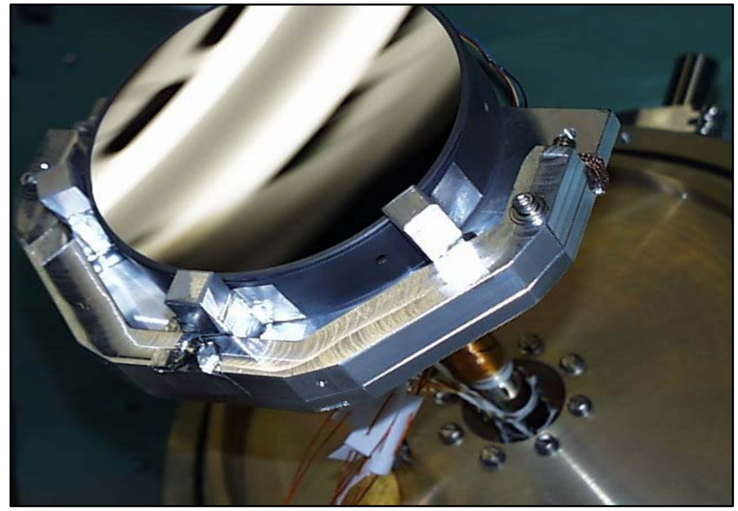
"The quoted NGST/ISIM wave front requirement is 58nm stability, but for the first time we have a lightweight cryo optic (38nm) that is in that range."

Dr. Dave Content



McCarter 12.5 cm SILICON SPHERICAL MIRROR

100% (full) aperture			piston/ tilt removed
subtraction	**PV**	**RMS**	**PWR**
cold - (pre cold) warm	0.436	0.071	-0.047
cold - (post cold) warm	0.598	0.071	-0.053
80% (clear) aperture			**piston/ tilt removed**
subtraction	**PV**	**RMS**	**PWR**
cold - (pre cold) warm	0.345	**0.057**	0.068
cold - (post cold) warm	0.325	**0.053**	0.066
post cold - pre cold	0.094	0.014	0.001

Goddard Space Flight Center

Test Results – Courtesy of Dr. Dave Content

AlMgF2 Coating Stress on Lightweighted SCSi Mirror

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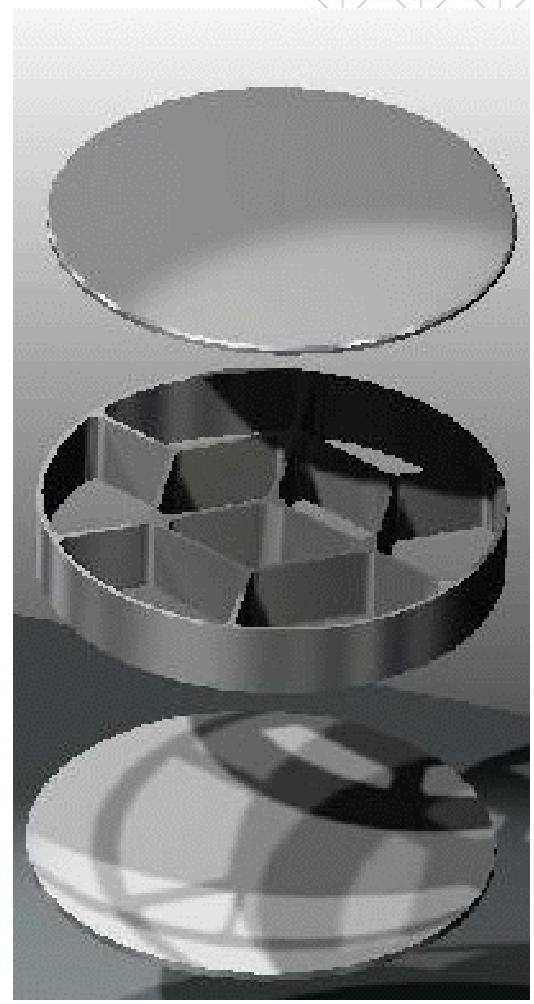
- Coated a lightweight Si mirror (exploded view at R)
  - Coating of AlMgF2 as per FUV Hubble optics
  - Applicable to many UV missions, and similar to others (e.g. AlLiF)
  - Measured wavefront before and after coating
  - Upper limit of wavefront change is 10 nm rms
  - Used this small lightweight sandwich mirror as substitute for the Kodak mirror



Optics

Goddard Space Flight Center

waves @633nm	before		after		difference	
	rms	pv	rms	pv	rms	pv
full aperture	0.079	0.457	0.067	0.391	0.015	0.128
90% aperture	0.067	0.332	0.063	0.301	0.013	0.084

Note: .015 wave = 9.6nm

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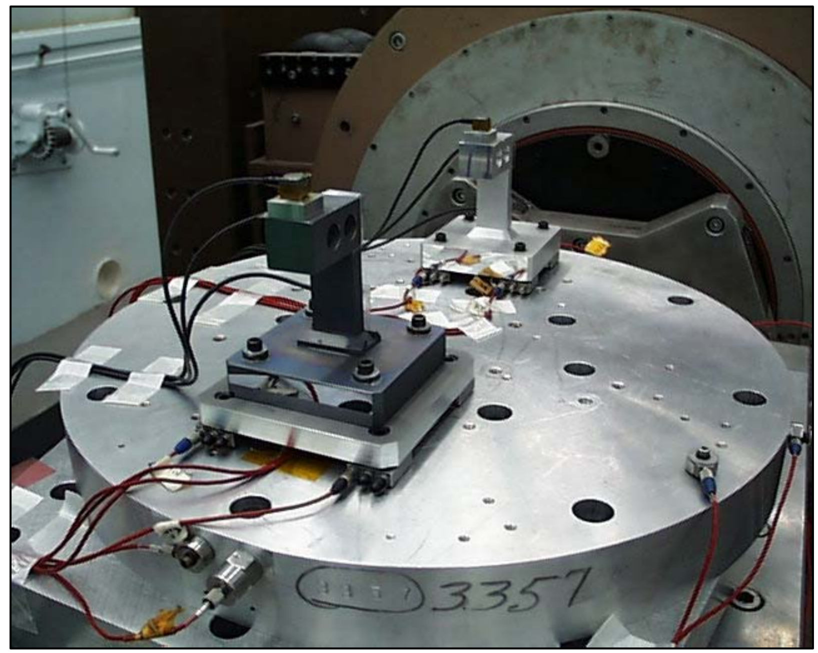
Test Results –
Shake/Tap Test at GSFC and ManTech

MANTECH ADVANCED SYSTEMS INTERNATIONAL

Silicon Sample		Aluminum Sample	
Pre Test		Pre Test	
Hz	10.8	Hz	3.4
V	19.9	V	-33.3
Post Test		Post Test	
Hz	10.9	Hz	-4.1
V	19.8	V	-37.3
Variation		Variation	
Hz	0.1	Hz	7.5
V	0.1	V	4

All measurements in arc seconds



Goddard Space Flight Center

Optics

NASA

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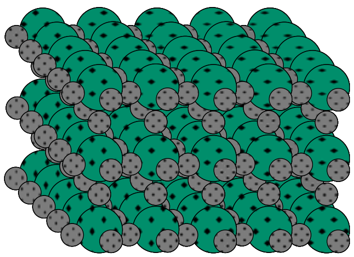
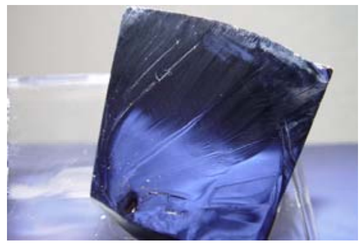
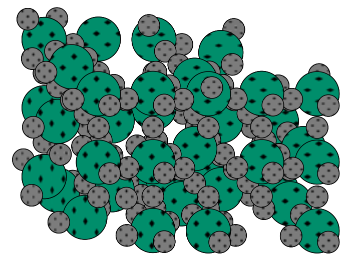
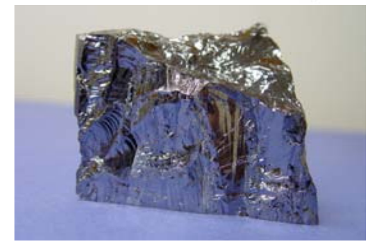
SCSi Properties

SCSi Cubic Structure

Polycrystalline Silicon Structure

According to Dr. James Boyle, co-founder of Silicon Crystals, Inc., growing polycrystalline silicon or depositing polycrystalline silicon onto a substrate "introduces grain boundaries […] resulting in critical performance deficiencies [and] wide variations of producibility".

Mirror Material	Thermal Expansion Coefficient	Thermal Conductivity	Density	Specific Heat	Elastic Modulus	Poisson's Ratio	Figure of Merit
	$\alpha(10^{-6}/^{o}C)$	k(W/cm-ºC)	ρ(g/cm)	Cp (J/g-ºC)	$E(10^{6}psi)$		α/k (cm/MW)
Single Crystal Silicon	2.10	1.53	2.33	0.753	24.5	0.26	1.37
CVD fine grain polycrystalline silicon	2.67	0.84	2.335	0.177	23.3	0.24	3.18

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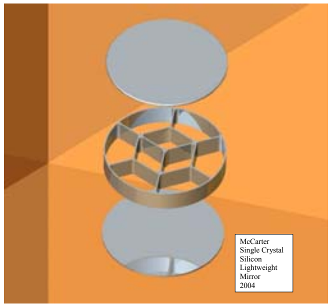
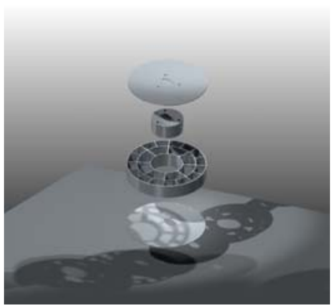
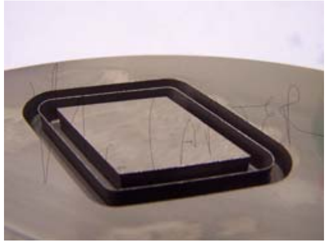
Additional Applications

Mirrors with Differing Aerial Densities







- **Robust**- Solid
- **Semi-robust** -
.750-.875 webbing
- **Lightweight** -
.035-.055 webbing
- **Featherweight** -
.008-.010 webbing

Silicon Carbide Flange with McCarter Superfinish

Complex Geometries