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Actively cooled silicon mirrors

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Abstract

The performance advantages of using silicon for actively cooled mirrors are developed through a comparison with molybdenum mirrors, the type used most extensively for high-energy CW laser applications.* In particular, maximum temperatures and distortions are related to a power loading parameter Factors which are likely to limit the operating capabilities of both types of mirrors are considered to assess their impact on attainable performance, as compared to potential performance Because silicon has not been used extensively for demanding thermal structural applications, mechanical property data has been quite limited This paper summarizes recently generated property data for single crystal Particular emphasis was placed on short-time strength because of the paucity of such data in the literature The test specimens used were processed in the manner expected to be employed for actual mirror components In this way, the strength test results should represent the behavior of the brittle silicon material in its as-used form By considering the performance potential of silicon mirrors and the properties of this material, it is possible to outline the potential advantages of such optical elements and to identify the challenges which must be met if actively cooled silicon mirrors are to become a reality

Why Silicon?

The selection of a construction material for high-energy laser mirrors requires consideration of many material properties and parameters References 1 and 2 discuss important factors and figures of merit which aid in choosing materials for mirrors or various types The design objective is to minimize distortions induced by applied loadings while avoiding degradation of the reflective coating For an actively cooled mirror of modest size, the loadings of primary concern are absorption of thermal energy from the incident beam and pressurization of the internal coolant Thermal distortion is of two types, beam mapping and bowing The beam mapping contribution is due to thermal growth and is strongly influenced by local heat input variations. Bowing is an integrated effect of thermal growth of the mirror face Both are minimized by a small coefficient of thermal expansion and a small increase in temperature due to heat flow over a short distance. High thermal conductivity minimizes the temperature rise through the mirror face and structure under both transient and steady-state operating conditions Bowing is minimized by a thick backup structure of high modulus of elasticity as well Pressure induced distortions are minimized by a large modulus of elasticity, low stress levels, and short distances Degradation of the reflective surface is avoided by keeping its temperature relatively low; thermal conductivity is the most important substrate material property in this regard.

In minimizing distortions, stresses in the mirror tend to be relatively low except in the mirror face itself Because the backup structure of the mirror remains cool, the temperature rise of the mirror face induces potentially high compressive stresses These compressive stresses are minimized by a small coefficient of thermal expansion, low modulus of elasticity, and high thermal conductivity If the induced stresses exceed the microyield stress, σ_{my}, permanent deformation will result and the mirror may be damaged beyond usefulness. Therefore, materials with a high microyield strength are desirable

With these considerations in mind, it is appropriate to compare several classes of materials to assess their potential, see Table 1 Although the candidates are listed in decreasing desirability with regard to thermal distortion, this is not the only consideration The chopped fiber carbon/carbon composite was eliminated from our consideration because of its low modulus of elasticity, low σ_{my} and immaturity of development status. Silicon is the most attractive construction material with regard to thermal deformation, thermal stress, and density parameters As compared to molybdenum, the use of silicon would reduce thermal distortion by a factor of approximately two but would experience about twice the pressure induced distortion With advanced mirror design concepts, it is possible to limit the pressure induced distortion to about 10% of the total for molybdenum mirrors and about 20% of the total for silicon mirrors Therefore, silicon's shortcoming in this regard is not a significant penalty Note that silicon is among the most desirable materials with regard to dynamic response, where it is inferior only to beryllium and silicon carbide.

Although material parameters are useful for comparing a large number of materials and for making selections, they are not accurate indicators of relative performance among specific materials Accurate comparisons require detailed analyses of realistic geometric configurations and considerations of temperature dependent material properties. Such analyses were conducted to compare silicon and molybdenum mirrors of identical geometric configuration subjected to a range of absorbed heat loads and coolant flow rates At current flux levels, the distortion of the silicon mirror would be 45-50% of that for the molybdenum mirror of identical design, depending upon the particular flux level and coolant flow rate Because the thermal conductivity of silicon decreases more rapidly with increasing temperature than that of molybdenum, the superiority of silicon tends to decrease slightly as mirror face operating temperature increases

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Table 1. Property Parameters Identify Attractive Materials For Cooled Laser Mirrors

Candidate Material	Relative Performance Parameter (1) $(k/\alpha) \times 10^{-6}$	$E \times 10^{-6}$	$(E/\rho) \times 10^{-6}$	$k/\alpha E$	$\sigma_{my} \times 10^{-3}$	ρ
Carbon/Carbon (Chopped fiber)	300	2 5	34	120	0 25	0.072
Silicon	50	24	286	2 08	16	0 084
Tungsten	38	59	86	0 65	60	0 70
Molybdenum	26	47	127	0.55	35	0 37
Copper	25	17	53	1 47	3	0 32
Silicon Carbide	12	55	500	0 22	30	0 11
Beryllium	12	42	627	0.29	17	0 067
Aluminum	8	10	100	0 80	25	0 10
Be Copper	7	19	63	0 37	25	0 30
Nickel	5	30	94	0 17	10	0 32

(1) High values desired except for density

k/α Thermal growth and bowing distortion parameter
E Pressure and bowing distortion parameter
E/ρ Natural frequency and inertia loading parameter
$k/\alpha E$ Thermal stress parameter
σ_{my} Microyield stress, estimated in most cases, permanent distortion parameter
ρ Density, mass parameter

The Challenge

In contrast to other candidate materials which are used in complex configurations for various thermal and mechanical applications, major uses of silicon have involved simple macroscopic shapes associated with semiconductor devices and solar cells Uncooled optical applications of silicon usually involve simple configurations and only modest loadings The lack of demanding thermal or mechanical design applications for silicon has precluded the type of data base and experience with fabrication methods needed for complex component configurations subjected to severe loadings Nevertheless, available material property and fabrication method data bases were evaluated and served as a foundation for generating the information needed to design and produce actively cooled silicon mirrors

The semiconductor behavior of silicon and its cubic structure stimulated sufficient interest in its properties, over the years, to provide a relatively good data base with regard to at least some of the information needed Table 2 summarizes the status of property information at the start of the silicon mirror investigation Gaps are identified; expansion of this data base is discussed later One major need was to relate strength to the type of surface finish expected to be produced on mirror components Another was to evaluate resistance to cavitation erosion damage which might be induced by high-speed coolant flow needed for high heat transfer coefficients

Table 2 Only Limited Property Data Was Available At The Start Of The Investigation

Property	Initially Available Data	Comment
Tensile Strength	10 to 60 ksi	Must relate to surface finish
Compressive Strength	70 to 80 ksi	Not expected to be critical
σ_{my}, Tension	–	Can be estimated
σ_{my}, Compression	–	Use tension σ_{my} initially
Modulus of Elasticity	16 to 28 x 10^6 psi	Requires resolution
Poisson Ratio	0 20 to 0 28	Requires resolution
Hardness	7 Mohs	Adequate
CTE	2.3 to 2.6 x 10^{-6}/K	Requires resolution
Thermal Conductivity	1.4 to 2 0 w/cmK	Requires resolution
Specific Heat	0 18 cal/gK	Adequate
Specific Gravity	2 33 g/cc	Adequate

Available material property data suggested that silicon would be an attractive material for cooled laser mirrors; this base was expanded to provide greater confidence in design A more significant challenge was posed in the fabrication area Despite the differences in configurational features expected for cooled laser mirrors and prior silicon components, some transfer of useful data was expected Table 3 summarizes approaches for material removal and joining which provided a starting point for the development activities that are currently underway Even though many of the techniques used for semiconductor and solar cell applications were expected to be adaptable to the mirror structure, the degree of adaptability to mirror configurations was difficult to assess. Therefore, a number of approaches were pursued concurrently so that those most appropriate for particular internal design configurations could be selected

Table 3. Prior Applications For Silicon Provide Data Base For Fabrication Techniques

Material Removal	Method	Comments
Grooves/Lands	• Chemical milling (etching)	1 to 1000 μm deep/high, down to 1 μm wide
	• Gaseous milling (plasma, ion)	Down to submicron dimensions, shallow
Holes	• Diamond coated tools	Limited application
	• Ultrasonic impact grinding	Limited application
Slicing	• Diamond coated I D. saws	Stock to about 10 inches
	• Diamond coated O D saws	Stock to about 30 inches
	• Diamond coated wires	Stock up to 36 inches
Dicing	• Diamond coated O.D. saw	Shallow cuts
Contouring	• Diamond coated grinding wheels	Lens, mirror and dome blanks
Lapping	• Conventional laps	Wafers, solar cells, optics
Polishing	• Conventional machines	Wafers, optics
Joining		
Die Bonding	• Eutectic solder	Requires scrubbing action
	• Epoxy	Lower cost, lower temperature
Leads	• Solder	Requires prior metallization of silicon
	• Weld	Requires prior metallization of silicon
	• Diffusion bond	Requires prior metallization of silicon
Cover Glass	• Electrostatic glass bonding	Modest temperature, for solar cells
	• Glass bonding	High temperature
Furnace Furniture	• Glass bonding	High temperature

Internal Design Features

In selecting material removal and joining techniques it is necessary to consider possible internal configurations for coolant flow passages and operating temperatures The values presented here are considered to be representative of cooled mirrors of up to about 10 inches in diameter. There is no intent to include all possible concepts and configurations. As shown in Figure 1, three regions of the mirror have significantly different requirements with regard to material removal because of the proportions and dimensions involved. In the heat exchanger region geometry is relatively fine with passages depths of between 0 010 and 0.030 inch and widths usually two or three times the depth. Both rectangular or hemicylindrical configurations are used Webs between the coolant passages may be 0 010 to 0 030 inch wide. For some mirror configurations, the mirror face is supported on posts which may range in diameter from 0.010 to 0.100

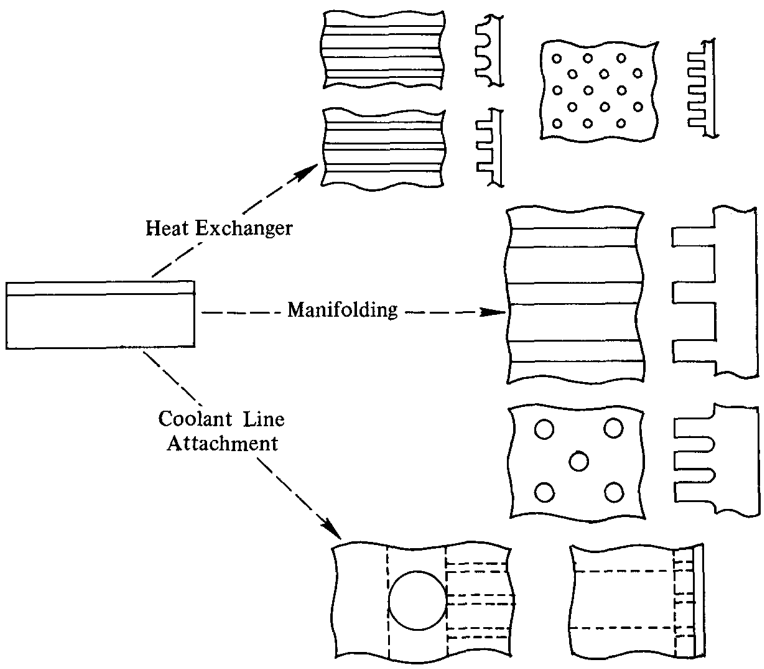

Figure 1. Internal Design Features Of Cooled Mirrors

inch. The manifolding portion of the mirror involves coarse geometry by comparison Passages may range from 0.10 to 0.50 inch deep. Webs may be from 0 05 to 0 25 inch in width. Some manifolds may incorporate posts of up to 0 25 inch in diameter The third region of geometric concern involves holes in the backup structure for attachment of coolant line fittings and/or flow control. For the first purpose, hole diameters may range from 0 25 to more than 1 00 inch For flow control purposes, hole diameters are generally less than 0 12 inch

For most current water cooled mirrors temperatures of internal joints are not likely to exceed 330K (about 150F) Joining techniques which provide strength levels of between 3,000 and 5,000 psi at operating temperature are required. High-reflectivity dielectric coatings will limit maximum mirror face temperature to about 500K; but, if a lower reflectivity metallic coating can be accepted, the allowable temperature may be increased somewhat.

Material Removal

Chemical milling, machining with diamond coated tools, electrical discharge machining, grit blasting, and ultrasonic impact grinding are material removal techniques that have been applied successfully to various classes of brittle materials. With chemical milling, or etching, very fine geometric configurations can be provided to exacting tolerances. Where geometric features are not extremely fine, machining with diamond coated tools is used most widely for brittle materials. Electric discharge machining has been used to produce configurations of fine detail in conductive materials Its applicability to silicon was in doubt because of the low electrical conductivity. Grit blasting can be used for reclaiming silicon wafers, so its evaluation seemed warranted Ultrasonic impact grinding, in a sense a sophisticated version of grit blasting, is used for hard materials both metallic and nonmetallic Here, the grit is transported as a slurry which is made to impact the work piece by the vibration of a suitably shaped tool at ultrasonic frequency.

Chemical milling experiments were conducted using the etchants and photoresists listed in Table 4 For many of the etchants the composition was varied as was the temperature of the bath The influence of such variations on the etch rate and the durability of the photoresist were of primary importance. Many of the etchants were found to be suitable for producing simple configurations of relatively modest depth In no case was it possible to obtain a chemically milled depth greater than 0.008 inch before general degradation of the photoresist Under optimum conditions, the amount of lateral etch was slightly less than the depth of etch If the patterns of interest had been simple straight passages, proper orientation of the silicon material in combination with anisotropic etches should have produced somewhat deeper coolant passages Because our coolant passage configurations are complex, it is necessary to rely on isotropic etchants The relatively shallow depth attainable with the chemical milling technique was considered to be unsuitable for removing the material necessary to form the coolant passages.

Table 4. Etchant And Photoresist Candidates Were Unable To Produce Complex Coolant Passage Patterns

Etchants	Photoresists
Nitric/Hydrofluoric/Water	Kodak KPR-3
Nitric/Hydrofluoric/Acetic	Kodak MX-752
Chromic/Hydrofluoric	Dynachem Laminar GT
Potassium Hydroxide	Dynachem Laminar EO

The coarse nature of the geometry associated with the manifolding in the backup structure of the mirror suggested the possibility of machining with diamond coated tools. Milling, core drilling, and surface grinding techniques were evaluated using tools coated with diamond grit sizes from 220 to 600. The coarser tools provided faster material removal rates and a surface finish considered adequate for the silicon mirror application. The finer grit tools tended to quickly fill with silicon dust which degraded cutting performance

As would be expected, high-purity silicon cannot be cut with electrical discharge machining It is not until impurity levels corresponding to an electrical resistivity of about 0.1 ohm-cm is reached that satisfactory operation is possible The resultant surface finish is dependent on the machine settings. When low-resistivity material is used, wire cutting and conventional EDM tools could be used to produce relatively fine geometric details

Studies of the grit blasting technique were relatively limited. Despite its brittle nature, cavities could be cut into silicon. Specific complex geometric features were difficult to produce because of masking problems Lines of various widths could be produced but depth was difficult to control.

Ultrasonic impact grinding was investigated also Geometric features such as slots and webs could be produced with widths of 0 010 inch to depths (or heights) of 0.020 inch, the deepest cut evaluated for narrow slots. With coarser geometries, it was possible to cut to depths greater than 0.25 inch. The surface finish was finer than that produced with 220 grit diamond tools and only slightly coarser than that produced by a 600 grit ID saw blade. Tooling costs were high compared to conventional diamond coated cutting tools.

As expected, the lapping of silicon surfaces was a simple operation It was possible to remove several thousandths of an inch per minute while retaining a good surface finish

As will be discussed later under mechanical properties, the surface finish has an influence on the strength of silicon. The various material removal techniques, other than chemical milling, introduce surface and subsurface damage which adversely influences strength. To remove this damaged zone, it is necessary to etch or chemically mill the detailed parts after machining. The isotropic etchants used for chemical milling are appropriate for damage removal as well

Material removal with diamond coated tools was found to be most cost effective More than four-hundred test specimens of various types have produced by this technique. Figure 2 shows some of them.

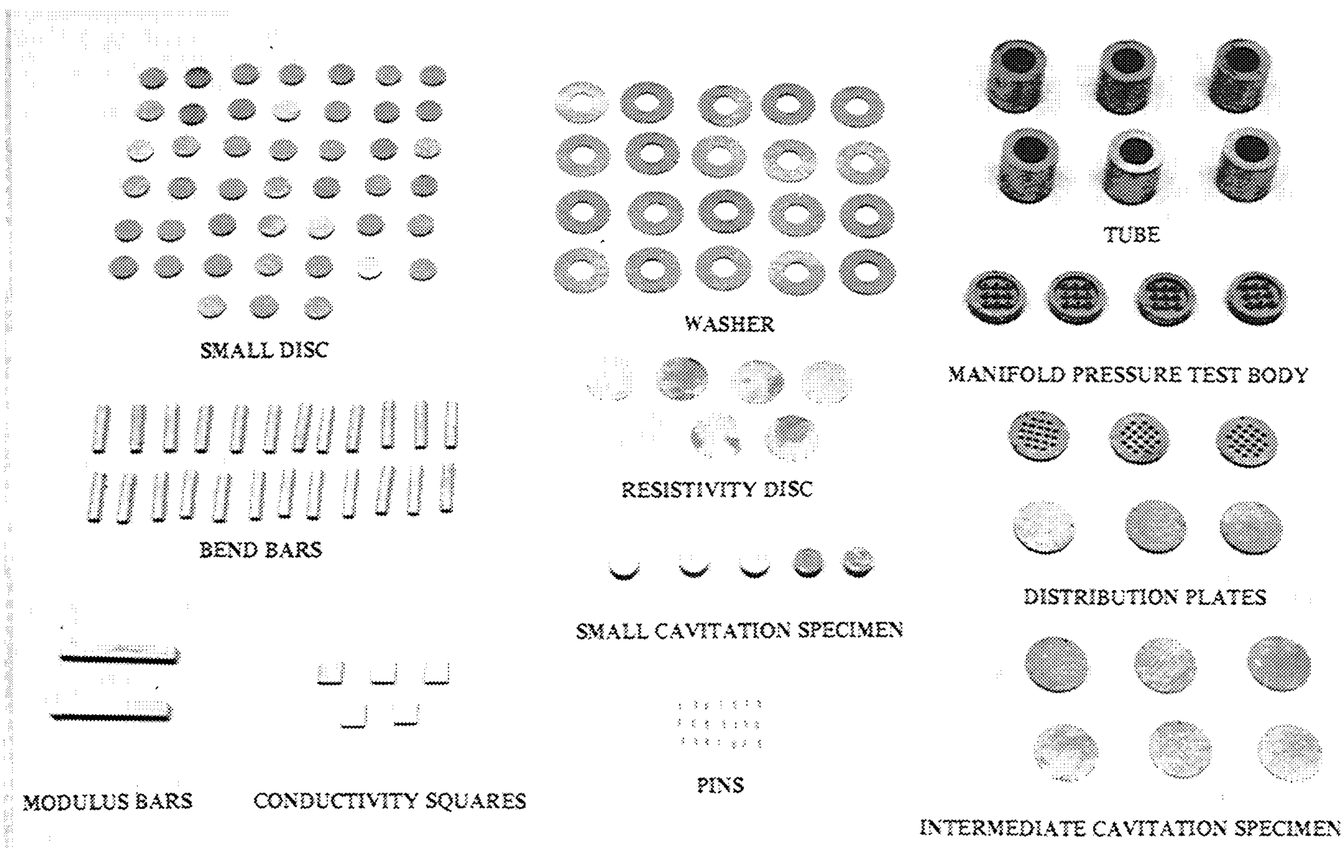

Figure 2. Silicon Test Specimen Configurations

Joining

The greatest challenge in adapting silicon technology to an actively cooled mirror was the identification of a process for joining the detailed parts into a usable leak-free assembly The intricacy of the internal flow passages precludes mechanical joining For present silicon applications, the predominant joining techniques are adhesive bonding, soldering, and glass bonding. Studies are underway in each of these areas, but the optimum approach has not been established yet

Operational temperatures at mirror joints are low enough for the use of polymeric adhesives The desirable characteristics of high strength and good ductility can be found for many adhesives with acceptable cure temperatures Major disadvantages are control of adhesive placement, high coefficient of thermal expansion, dimensional instability, and degradation when exposed to moisture These shortcomings preclude the use of adhesive bonding for general assembly operations but it may be suitable for certain joints such as small bearing plates remote from the clear aperture and metallic coolant line fittings

Prior to the extensive use of adhesives for die bonding, this function was accomplished by gold eutectic soldering techniques. Adequate bond strengths were achieved for small components; a rubbing action was incorporated to promote joining Our experience with the gold eutectic alloys was discouraging. The relatively large size of the parts of interest precluded the introduction of the rubbing action In a static environment, wetting and joint strength were poor

Conventional solders will not wet silicon but metallization of the silicon permits consideration of many solder candidates to achieve strong ductile joints. A literature review identified a number of potentially attractive metallization systems, as listed in Table 5 No meaningful strength data was found so selections were made based on resistance to various environmental conditions, the titanium/palladium/gold system was the primary choice with titanium/palladium/silver as a backup To minimize leaching of the topcoat initial interest was focused on solders which contained a relatively high indium content Candidates are listed in Table 6 Some were eliminated on the basis of wetting and flow experiments Those which were selected for strength testing are identified in the table; note that both high strength and low CTE types were included

Screening tests were performed using the specimen configuration of Figure 3 The joint between the washer and disk was narrow to simulate representative joints within the mirror. The disk was relatively thick to minimize bending distortion at the joint The washer was large to minimize the stress level in the adhesively bonded joint The test results are presented in Table 7 In most cases, the failures were in the solder joint and involved a small amount of silicon pullout Our data did not agree well with data published by the solder supplier as can be seen by comparing strength results in Tables 6 and 7 Strength differences could be due to differences in specimen geometries or substrates

Table 5. Prior Studies Identified Promising Metallization Systems For Silicon

Metallization	Application
Ti/Pd/Ag	Solar cells
Ti/Pd/Au	Microelectronics
Ti/Pt/Au	Microelectronics
Ti/Mo/Au	Microelectronics
NiCr/Au	Microelectronics
NiCr/Pd/Au	Microelectronics
NiCr/Cu/Pd/Au	Microelectronics
Mo/Au	Microelectronics

Table 6. High Indium Solder Candidates Minimize Leaching Of Precious Metal Films (1)

Alloys	Liquidus K	Solidus K	C.T.E. (2) At 293K	Thermal Conductivity, (1) w/cm K At 358K	Tensile Strength, (1) psi
52 In/48 Sn	390	390	20	0 34	1720
80 In/15 Pb/5 Ag (2)	422	415	10	0 43	2550
70 Sn/18 Pb/12 In (2)	435	435	24	0.45	5320
70 In/30 Pb (2)	447	433	28	0 38	3450
60 In/40 Pb (2)	458	447	26	0.19	5000
50 In/50 Pb (2)	482	453	27	0 22	4670
90 In/10 Ag (2)	510	414	15	0 67	1600
75 Pb/25 In (2)	537	523	26	0.18	5450

(1) Properties as defined in vendor literature (2) Selected for screening

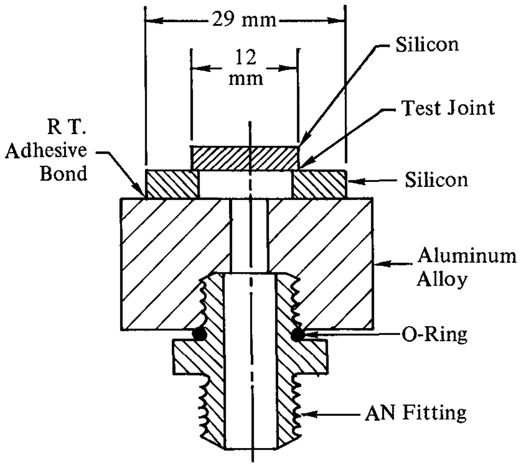

Figure 3. Joint Strength Screening Specimen

Table 7. Measured Solder Strengths, Compare With Vendor Predicted Tensile Strength Listed In Table 6

Solder Composition	Failure Stress psi	Comments
80 In/15 Pb/5 Ag	1340	Good Solder Flow
70 Sn/18 Pb/12 In	320	Poor Solder Flow, Scavenging
70 In/30 Pb	2080	Good Solder Flow
60 In/40 Pb	1000	Good Solder Flow
50 In/50 Pb	1700 to 2660	Good Solder Flow
90 In/10 Ag	1820 to 2800	Good Solder Flow
75 Pb/25 In	No Joint	Solder-Spongy and Dull

Table 8. Strength Of Soldered Joints Influenced By Leaching And Specimen Configuration 96.5 Sn/3.5 Ag + 62 Sn/36 Pb/2 Ag

Metallization Top Coat/ Electroplate	Stress In Joint At Failure, psi	Comments
Silver/None	2000 to 3800	Failed silicon washer
Gold/None	800 to 5800	Pulled off metallization
Silver/Silver	1400 to 3800	Failed silicon washer
Gold/Gold	2250 to 4000	Failed silicon washer

As our design studies progressed, it appeared that the indium containing solders would not have adequate strength. Emphasis was shifted to solders with high tin contents with results as shown in Table 8. The much higher scavenging tendencies of the tin based solders necessitated the use of an electroplated coating over the metallization, both silver and gold electroplates were evaluated A review of Table 8 indicates highly erratic results for the gold system prior to the use of the electroplating step This appeared to be due to variability in the amount of leaching that was experienced despite careful control of time and temperature. The strength test results for the gold electroplate seemed to be somewhat superior to those for the silver electroplate, although the strength results overlapped In almost all cases, failure shifted from the joint to the silicon washer so that the true strength of the solder system was obviously greater than the test results indicated

To obtain a more reliable indication of the true strength of the solder tests were run of soldered copper specimens of the configuration shown in Figure 3 Results show greater strength levels than found in the literature, 5600 to 6750 psi versus 4100 psi.

Work is continuing to definitize the strength characteristics of the metallized and soldered joint techniques and to define its degree of reproducibility

Glass bonding appeared to be a potentially attractive technique for assembling silicon details Although coefficient of thermal expansion of a glass bond rarely matches that of silicon, the differences are smaller than between solder and silicon Potential disadvantages of glass bonding include lack of ductility, potential for contamination of the silicon during firing, and low strength Available data indicated strength levels in the order of 2500 psi At the time of program initiation, such levels were considered to be adequate and some glass bonding trials were undertaken Strength levels were found to be less than 2500 psi for the samples tested. Inasmuch as the refinement of design requirements, by this time, indicated the need for higher strength further work on glass bonding was not pursued More recently, another glass composition was identified and our investigations have resumed with initially measured strengths of between 3800 and 4600 psi. Further work is in progress as a alternate to the solder joining approach.

Mechanical Property Data

The face of an actively cooled mirror experiences the highest induced stresses, but they are compressive and are not likely to cause structural failure. Although tensile stresses are usually much smaller, they are the ones that cause fracture of brittle materials such as silicon. Design allowable tensile strengths of such materials are usually sensitive to the character of the surface, so for our testing the strength specimens were machined in a way representative of the techniques expected to be used for actual mirror parts In addition to strength test data, modulus of elasticity and Poisson's ratio values are necessary for the computations of structural integrity and distortion

At the start of the investigations of silicon for the cooled laser mirror application, relatively little mechanical property data had been found in the literature Available information was sufficient for preliminary design purposes but there was little assurance that the published data would represent attainable strength of mirror components Although the tensile stresses within the mirror were expected to be less than 5000 psi, a minimum allowable tensile strength was difficult to define Therefore, concurrent with preliminary design studies and a continuing search of the literature, mechanical properties of single crystal silicon were measured at the University of Dayton Research Institute, UDRI.

A total of ninety-four single crystal silicon bars were fabricated and tested in four point bending at 75F and 550F Some tests were conducted with metallized coatings on the tensile surface of the bend bars, because metallic coatings were expected to be applied to the surfaces of some of the silicon parts The diamond coated tools used to machine the specimens had the same grit size as the tools expected to be necessary for producing laser mirrors details Surface and subsurface damage was removed by chemical etching Reference 5 indicated the importance of the chemical etching after machining in order to minimize the variability of strength and to increase the average strength value

Results of the bend tests are summarized in Table 9 The tests were run at different times with samples produced by several variations of the basic technique as indicated. The results indicated that the chemical etching was effective in eliminating the influence of the diamond machining as can be seen by the similarity of average and standard deviation values for groups of samples produced with different diamond grit grinding wheels.

Table 9. Etching Minimizes Strength Dependence Of Silicon On Diamond Grit Size Of Machining Tools

Grit Size On Grinding Wheel	Temperature, K	Number Of Samples	Bend Strength, ksi Average	Bend Strength, ksi Standard Deviation
220 Grit, Etched	300	24	16 8	4 56
	585	23	20.6	5 09
220 Grit, Etched,	300	10	21 8	2 6
Metallized	585	9	17.7	4 2
600 Grit, Etched	300	14	19 8	4 7
	585	14	19 1	6.7

The only significant difference in the various test results at room temperature was due to the presence of the metallized coating For the coated bars, the average strength increased slightly and the standard deviation was reduced. This suggests a low level of compressive stress induced by the metal deposition. The closer similarity of the coated and uncoated strength characteristics at elevated temperature tends to support the premise of slight residual compressive stresses at room temperature

On the basis of these test results, a design allowable strength in tension was expected to be in excess of 5000 psi

Although the bend strength results were the most interesting of the mechanical property measurements, determinations were made of modulus of elasticity and Poisson ratio Modulus values were generally in the range of 28 x 10^6 psi although for one sample, the modulus was measured as 18 x 10^6 psi. Repeated measurements of this test bar always yielded essentially the same results The reason for this unusual behavior was not identified. Measured values of Poisson ratio ranged from 0 20 to 0.28, in good agreement with other published data.

Thermal Properties

The two thermal properties of most importance for the design of cooled laser mirrors are thermal conductivity and coefficient of thermal expansion. Reference 6 provides extensive data for the thermal conductivity of silicon as influenced by many detailed variations of the basic material. The data on coefficient of thermal expansion is somewhat more limited Thermal conductivity and coefficient of thermal expansion testing was performed in support of the silicon mirror investigations; Figures 4 and 5 present the results The thermal conductivity was basically in agreement with the information provided by Reference 6 and that the coefficient cf thermal expansion measurements yielded values slightly lower, but within about 10%, of other published information, References 7, 8 and 9.

Cavitation Resistance

Cavitation resistance is a potentially important behavioral characteristic for which there was no data and no way to estimate the merit of silicon to this cooled mirror environment. Therefore, tests were conducted under an acoustic horn to obtain data which could be compared with molybdenum. Test samples were 0 62 inch in diameter. The area impacted by the acoustically generated bubble was 0.50 inch in diameter.

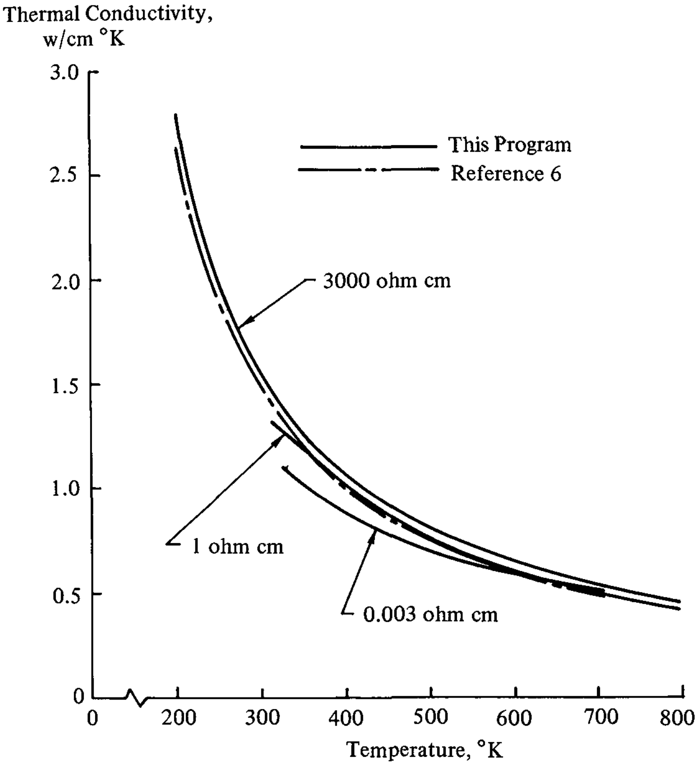

Figure 4. Purity Level Influences The Thermal Conductivity Of P-Type Boron Doped Single Crystal Silicon

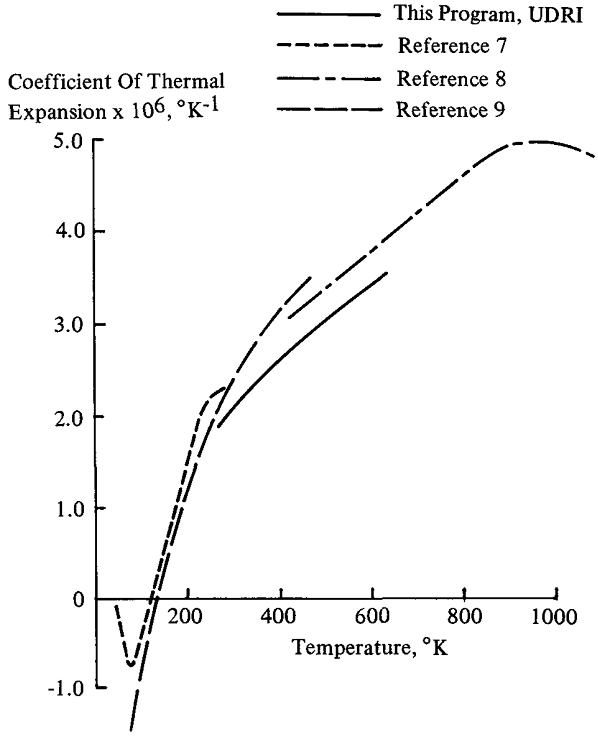

Figure 5. Single Crystal Silicon Has Low Coefficient Of Thermal Expansion

Initially, the erosive losses were uniform for both molybdenum and silicon. After extended exposure pits began to form in the silicon. The time required for pitting to start was related to the initial surface finish, the smoother the as-machined surface the longer it took for pits to form. Because the test conditions cannot be related to mirror flow conditions, quantitative data can be misleading. It is sufficient to state that for the roughest silicon surface tested, machined with a 220 grit diamond tool, the cavitation erosion rate was about twice that for molybdenum. Inasmuch as there are no known failures of molybdenum mirrors that were induced by cavitation this mechanism is not likely to have a significant influence on silicon mirrors.

Conclusions

Although high-purity silicon has been used primarily for electronic and solar cell applications, its unique properties such as a low coefficient of thermal expansion and a high thermal conductivity indicated its potential usefulness for actively cooled laser mirrors. Analytical investigations indicate that silicon mirrors will experience only about one half of the distortion of a molybdenum mirror of the same design. Fabrication studies have shown that the geometric configurations required for cooled laser mirrors can be produced in the silicon material Joining studies that are in progress have been encouraging and suggest success in this area as well As part of the investigations, the material property data base has been expanded to the point where actively cooled silicon mirrors can be designed with confidence.

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