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Rapid fabrication of lightweight ceramic mirrors via chemical vapor deposition

Jitendra S. Goela and Raymond L. Taylor
Morton Thiokol Inc./CVD Incorporated, 185 New Boston Street, Woburn, Massachusetts 01801

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Lightweight Si/SiC mirrors of nominal diameter 7.5 cm have been fabricated via a scalable and rapid, chemical vapor deposition (CVD) process to demonstrate the CVD mirror fabrication technology. These mirrors consist of a faceplate of either Si or Si-coated SiC and a lightweight backstructure made of either Si or SiC. The mirrors were polished to a figure better than 1/5th of a wave at 0.6328 Å and a finish of better than 10 Å rms. A procedure for fabricating these mirrors is described. The CVD fabrication process is fast and has the potential to yield several mirrors in a few weeks time from a single reactor. The CVD mirror fabrication technology is quite general and can be extended to include mirrors of other ceramic materials such as TiB_2 and B_4C.

A continuing need exists to develop new methods and technologies which are capable of producing high performance optics in large and small sizes rapidly, efficiently, and in a cost effective manner. Large, lightweight optical components, in particular, mirrors, are required for many space-based systems such as light detection and ranging, astronomical telescopes, solar collectors, high-energy particle, ion and laser beam concentrators, and deflectors. The performance of small optics can be improved if aspheric surfaces or low *f*-number optics are used. The current optical fabrication processes are quite slow and time consuming, and are not capable to rapidly produce high performance optics, particularly, large ($\geqslant$1-m-diam) mirrors.

Recently, a spin casting technique has been used to fabricate 1.2-m-diam and 3.5-m-diam glass mirror blanks containing lightweight honeycomb cells.[1] Although this technique is relatively faster than the conventional mirror fabrication methods and produces lightweight mirrors, the weight of these mirrors is still an order of magnitude more than required for many space applications. Further, the spin casting technique is unsuitable to fabricate large mirrors of advanced ceramics such as SiC, TiB_2, and B_4C that have high melting points. However, these latter materials have properties superior to those of glass for large lightweight optics. Other techniques such as casting of fiber-reinforced composites containing epoxy and plastics[2] and stretching of membranes over appropriate substrates are also currently under investigation to provide large mirrors.

In this letter, we report, for the first time, successful fabrication of lightweight ceramic mirrors via a chemical vapor deposition (CVD) process. Chemical vapor deposition can produce theoretically dense, highly pure polycrystalline materials which can be polished to a high degree of surface figure and finish. The CVD Si and SiC materials have been polished to a surface finish of 2 Å rms and 5 Å rms, respectively.[3,4] Further, a CVD process is scalable,[3,4] permits replication on suitable substrates to yield near-net shape parts,[3-5] and produces strong multilayer structures without having to use a bonding agent.[5] All these features of CVD technology are important in fabricating lightweight ceramic mirrors, as explained below.

Lightweight mirrors were fabricated from Si and SiC because both these materials have superior properties for mirror applications. Both Si and SiC are lightweight materials possessing a low value of thermal expansion coefficient and a high value of thermal conductivity. Silicon is attractive because it does not require any additional coatings for fabricating an actual optical figure with a high surface finish ($\sim$2 Å rms). Silicon carbide is attractive because it possesses very high structural efficiency, and it is stronger, stiffer, and harder than Si. Since the extreme hardness of SiC makes fabrication of optical surfaces in it slow and expensive, hybrid mirrors consisting of a silicon faceplate bonded to a SiC solid substrate or a honeycomb structure are currently under development for space applicatons. These hybrid mirrors combine the extremely high stiffness of SiC with the high polishability of Si. As one component of the hybrid mirror, Si is attractive because (i) its thermal expansion coefficient matches that of SiC over all anticipated operating conditions, and (ii) its modulus of elasticity is smaller than that of SiC. The first feature permits bonding or coating of Si to SiC without generating any bimaterial effects in the hybrid structure, while the second feature minimizes bending distortion in the mirror.

Figure 1 shows a flow chart of a CVD procedure that has been used to fabricate Si/SiC lightweight mirrors. These mirrors consist of a faceplate of SiC on which a coating of CVD Si has been applied, and a lightweight backstructure of SiC. First a mandrel is fabricated from graphite or any other suitable material such as SiC, Mo, W, or sapphire. On one side of this mandrel is fabricated a surface which is the "negative" of the actual mirror figure desired [Fig. 1(a)]. This mandrel is polished to a high degree of tolerance, coated with a mold release coating, such as a suspension of colloidal graphite and mounted in a CVD reactor [Fig. 1(b)]. In this reactor, the mandrel is heated to about 1300 °C and a mixture of CH_3SiCl_3 and H_2 in the ratio 1:4 is introduced to deposit a predetermined thickness of SiC. This SiC deposit acts as a faceplate for the Si/SiC mirror. The mandrel along with the SiC faceplate is then removed from the CVD chamber and the deposition side is cleaned without removing the faceplate from the mandrel. Since the SiC faceplate is

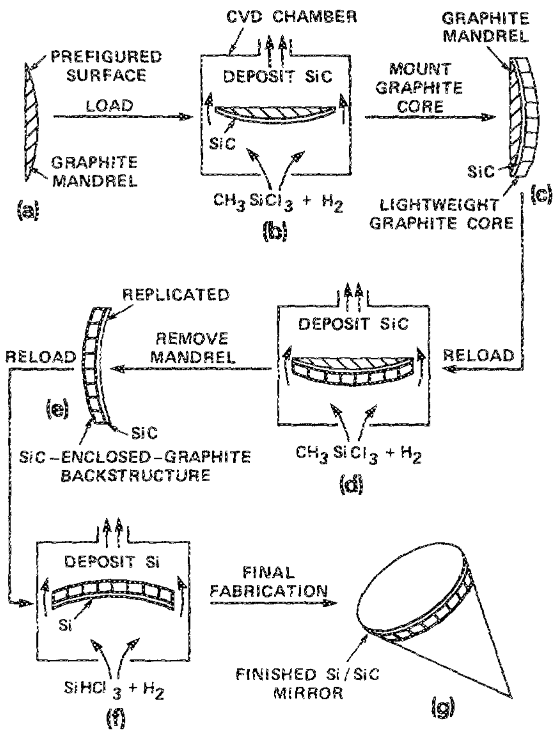

FIG. 1. Flow chart of CVD technique of fabricating lightweight Si/SiC mirrors: (a) fabricate mandrel, (b) deposit SiC to fabricate faceplate, (c) mount lightweight graphite core, (d) deposit SiC to fabricate backstructure, (e) remove mandrel, (f) clad Si, (g) final fabrication.

usually thin relative to its surface area, the graphite mandrel provides proper support during the cleaning operation. A hexagonal cell, honeycomb core is then fabricated from graphite ribs of thickness about 0.5 mm and bonded to the backside of the faceplate [Fig. 1(c)]. This graphite core has several small holes (Fig. 2) in the walls to further reduce the weight of the structure and also to disburse the reagents during CVD deposition. The assembly consisting of the graphite mandrel, the SiC faceplate, and the graphite lightweight core is then mounted in the CVD reactor and a layer of SiC is deposited onto the graphite core [Fig. 1(d)]. This deposition totally encloses the graphite core and also reinforces the bonding of the lightweight structure to the SiC faceplate. Next the mandrel is separated from the SiC faceplate [Fig. 1(e)] yielding a replicated figure on the faceplate. This replicated figure is within 100 μm when deposited on high-density graphite mandrels and within a few microns for sapphire and SiC mandrels. Since Si is relatively easier to polish than SiC, a coating of Si is applied to the mirror faceplate. The silicon coating on SiC is particularly desirable when graphite is used as a mandrel material. In order to apply the Si coating, the reactor is heated to about 1000 °C and a mixture of $SiHCl_3$ and H_2 in the ratio of 1:5 is passed through the deposition area [Fig. 1(f)]. After a sufficient thickness of Si is deposited, the Si/SiC mirror substrate is unloaded from the reactor. Finally, the near net shape mirror is optically fabricated to the desired level of figure and finish.

The aforementioned procedure has also been extended to fabricate lightweight Si and SiC/Si (faceplate of SiC and a lightweight structure of Si) mirrors. Figures 2 and 3 show some pictures of Si/SiC and Si mirrors of 7.5 cm nominal diameter fabricated by the above procedure. In Fig. 2 we show two pictures of flat Si/SiC mirrors. These mirrors have been polished to a figure of $\lambda/5$ at 0.6328 μm and a finish $\leqslant 10$ Å rms. One can see the flow holes in the lightweight structure. These flow holes reduce the weight of the mirror, provide passages for the reagents to flow, and also connect both sides of the SiC deposit. Thus, essentially, these holes act as "rivets" and produce a very strong and stiff lightweight structure. Another consequence of CVD deposition is that the cell walls are tapered with the thickest SiC coating away from the faceplate. This is also beneficial because it increases mirror stiffness without increasing its weight.

Figure 3 shows five different models of the lightweight mirrors comprising two flat and two curved Si/SiC mirrors and one Si mirror. The curved mirrors have a radius of curvature of 17.5 cm and the thickness of the faceplate in these models varies in the range 1.5–5.0 mm.

The scalability of the CVD mirror fabrication technology to yield mirrors in the 1.0-m-diam size range was investi-

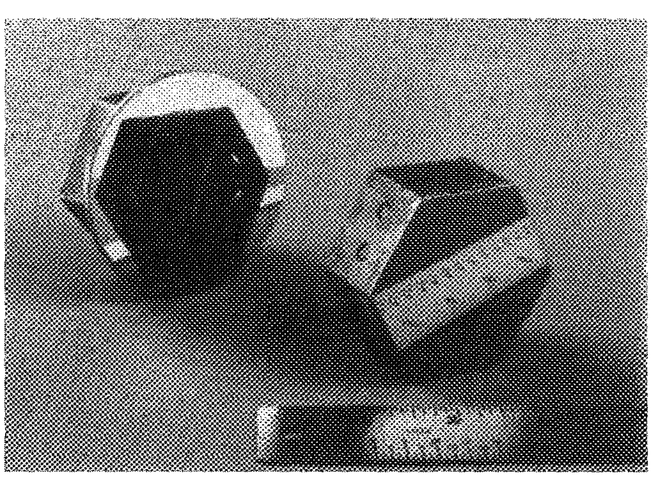

FIG. 2. Pictures of two flat Si/SiC mirrors fabricated via CVD.

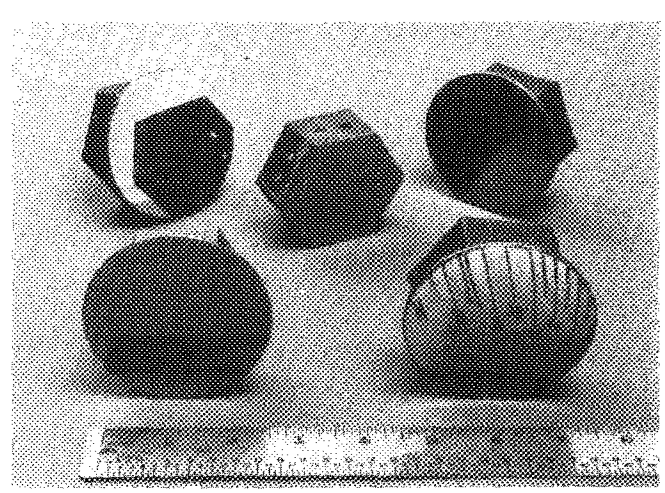

FIG. 3. Silicon and Si/SiC lightweight mirrors. Two mirrors on the right are curved. The front mirror on the left is made of Si.

gated. Relevant nondimensional CVD process parameters were identified and important scaling laws developed. These scaling laws show that there is no physical limitation on the scalability of the CVD process, except that a large size mirror will require a correspondingly large size CVD chamber. These scaling laws have been validated by fabricating a lightweight mirror substrate, 25 cm in diameter in our pilot plant size furnace. Currently efforts are under way to fabricate a 40-cm-diam curved Si/SiC mirror for NASA light detection and ranging applications. The surface of this mirror will be spherically concave with a radius of curvature of about 1.0 m.

Estimates for the production rate of these mirrors have been developed. In a single CVD reactor, one can mount three mandrels in series and fabricate three identical pieces simultaneously.[6] Based upon the fabrication approach described above, it takes three CVD depositions to fully fabricate these lightweight Si/SiC mirror substrates. Ideally, these three CVD depositions can be completed in about six weeks time thereby yielding three mirrors in six weeks from one furnace. Thus, on an average, one can fabricate one mirror every two weeks. This time scale is relatively independent of the mirror size since, in our approach, a large size mirror will require a correspondingly large size furnace. If additional furnaces are employed, the production rate of these mirrors can be further increased. This is in contrast to the fabrication of glass mirrors which can take several months to a few years to fabricate.

It is emphasized that the CVD mirror fabrication technology is quite general and mirrors of other ceramic materials can also be fabricated. For instance, advanced ceramic materials such as TiB_2 and B_4C possess physical, mechanical, and optical properties comparable to those of SiC for mirror applications. These materials can also be fabricated via a CVD process.[7,8] Consequently, for specific applications requiring some unique characteristics of these materials, SiC can be readily replaced with any one of these materials.

In conclusion, we have shown that 7.5-cm-diam flat and curved lightweight mirrors of Si or SiC can be fabricated via a CVD process. This process is scalable and has the potential to rapidly fabricate large mirror substrates of advanced ceramic materials.

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