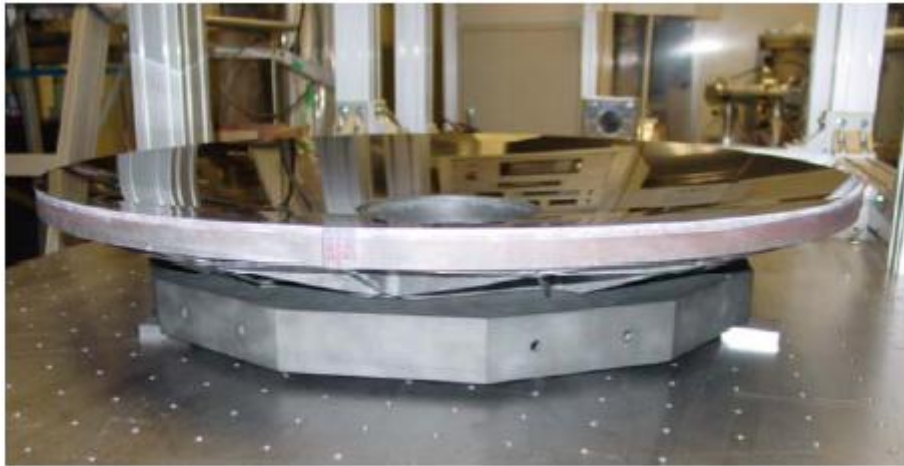


# Lightweighted telescope mirrors: Outstanding properties of Silicon Carbide

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**Figure 1-Silicon carbide polished mirror for SPICA**

## **Introduction:**

Nowadays, the willingness to always go further in the exploration of the Space and its celestial bodies requires the observation instruments sent in the Space to continuously improve their performances. Thus, the optics needs to get bigger to achieve higher spatial resolution, accuracy or light flux collection when scanning the Universe.

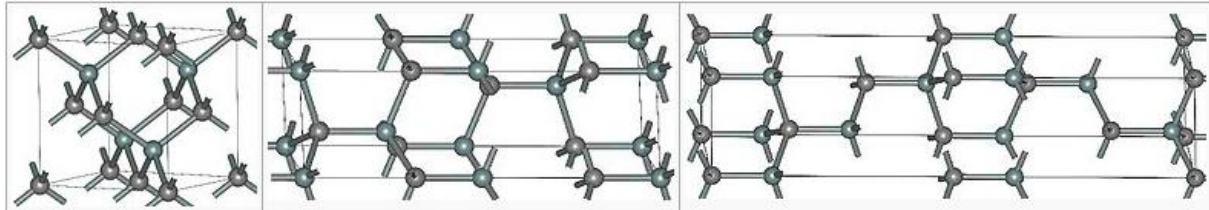
However increasing their size all the while with keeping the same high optical performances is at stake, and notably when each additional gram is tracked down. That is why, it was essential to find materials with very good optical, mechanical, thermal and lightweight properties such as Silicon Carbide (SiC) to meet ambitious research requirements. SiC is also a good resistant of space particles.

This tutorial provides an overview on the properties of SiC and its manufacturing for telescopes' mirrors application considering SiC is becoming the third generation space mirror material.

## I- Silicon Carbide properties

Silicon Carbide (SiC) is a compound of Silicon and Carbon. Its natural formation is due to electrochemical reaction between sand and carbon at very high temperature. Nowadays, SiC is industrially manufactured for many applications included the production of ceramics with outstanding mechanical properties.

SiC is composed of tetrahedral structures of Silicon and Carbon strongly bonded with each other in the crystal lattice which makes it a very hard and strong material.



(a) beta-SiC

(b) 4H-SiC

(c) alpha-SiC

Its mechanical and thermal properties presented in the following tables (Table 1 and 2) highlight its high stiffness, high thermo-mechanical stability. SiC density is comparable to Aluminum's but it is cheaper. And, even though it has higher density than the other material presented in these tables, SiC mirrors can be made lighter. Moreover, SiC mirrors, for instance, use fewer support points than glass mirror of the same size to reach a similar deflection amplitude.

| Material                                      | Young's Modulus (GPa) | Density (g/cm <sup>3</sup> ) | Specific Stiffness (10 <sup>3</sup> Nm/g) |
|---|-----------------------|------------------------------|---|
| ULE 7971                                      | 67                    | 2.21                         | 30  |
| Zerodur                                       | 92                    | 2.53                         | 36  |
| Silicon carbide (reaction bonded 30% silicon) | 330                   | 2.89                         | 114                                       |
| Silicon carbide (chemical vapor deposited)    | 465                   | 3.21                         | 145                                       |
| Beryllium 1-70                                | 287                   | 1.85                         | 155                                       |

Table 1- Mechanical properties of SiC, compared with other materials

| Material                                      | Thermal Conductivity $\kappa$ (W/mK) | Coefficient of Thermal Expansion $\alpha$ (10 <sup>-6</sup> /K) | Specific Heat $C_p$ (J/gK) | Thermal Diffusivity $D=\kappa/C_p\rho$ (10 <sup>-6</sup> m <sup>2</sup> /s) | Steady State Coefficient $\alpha/\kappa$ (10 <sup>-6</sup> m/W) | Transient Coefficient $\alpha/D$ (s/m <sup>2</sup> K) |
|---|--------------------------------------|---|----------------------------|---|---|---|
| ULE 7971                                      | 1.3                                  | 0.03  | 0.77                       | 0.8   | 0.023   | 0.039   |
| Zerodur                                       | 1.6                                  | 0.03  | 0.81                       | 0.8   | 0.019   | 0.038   |
| Silicon carbide (reaction bonded 30% silicon) | 155                                  | 2.4   | 0.67                       | 80.0  | 0.015   | 0.030   |
| Silicon carbide (chemical vapor deposited)    | 280                                  | 2.2   | 0.73                       | 119.5   | 0.008   | 0.018   |
| Beryllium 1-70                                | 216                                  | 11.3  | 1.92                       | 60.8  | 0.052   | 0.186   |

Table 2- Thermal properties of SiC compared with other materials

SiC has outstanding properties:

- It is barely sensitive to thermal distortions [low CTE and steady state coefficient], which means it does not expand significantly under temperature change and is quite stable thermally speaking.
- It is very stiff.
- It is a lightweight material.
- It has high isotropy property.
- It doesn't oxidize unlike other carbides
- It is relatively low cost (about 30\$/kg to 90\$/kg), which is preferred for large size parts or high-volume production.

However, SiC is brittle and has a tendency to shrink, moreover it only allows low structural complexity. Besides, SiC mirrors require large wall thickness and open back structure. Therefore, to address these issues, a carbon fiber reinforced Silicon Carbide composite, known as C-SiC, has been created. This composite allows extremely complex 3D structures design, much smaller wall thickness and open and closed back structure for lightweight mirrors. It also has a Weibull modulus higher than the other type of SiC (12.1 instead of 7.4 for other SiC composites).

## II- Manufacture of SiC mirrors

A randomly orientated carbon fiber bulk material is molded with phenolic resins at high pressure to form a carbon reinforced plastic blank. This material is then heated (1000° C) to create a rigid “green body”. This green body can easily be milled in order to give it the required shape with an accuracy up to 0.1 mm.

Once milled, the green body is heated under vacuum at a temperature allowing silicon to be in a liquid state ( $T > 1400\text{ }^{\circ}\text{C}$ ). The liquid silicon interacts therefore with the carbon matrix and carbon fibers previously manufactured in order to form a Silicon Carbide matrix. This phase is the *infiltration phase*.

The infiltrated mirror blank is now ready to be grounded and coated to adopt the required shape figure.

For *the coating phase*, different processes can be considered.

### Reaction bonded SiC (mix of alpha SiC and pure SiC)

To fabricate this material, alpha SiC is cast, dried and fired. After this process a porous SiC alpha mixture is re-fired after refilling the pores with pure Si (12 to 40%). The material obtained is therefore 100% dense. It is also possible to scatter SiC powder of various grain structures and sizes on the SiC alpha bulk material, the grains spread are randomly oriented within the crystalline material giving it isotropic properties. This method allows a wide range of physical, thermal and mechanical properties for complex and lightweight structures design.

### Hot pressed process and sintering:

In the hot pressed process, the particulates of alpha-SiC, with a size of the order of magnitude of the micron are heated at very high temperature (2000°C) and high pressure (1000-2000 atm) to consolidate the whole structure. With the help of sintering<sup>1</sup> techniques and grain growth inhibitor a quasi 100% dense bulk material is obtained. However this technique can only be applicable to small and simple shape structure. Moreover, a tremendous amount of machining is required to meet lightweight property of mirrors.

### Chemical Vapor deposited (CVD) or Chemical Vapor composite (CVC)

CVD is a process whereby films are formed on a substrate. It is performed at atmospheric or lower pressure and consists in immersing the substrate in a gas flow. Once gas particles are absorbed on the substrate, they react with one another to form a film of the material. The properties of the final films such as porosity highly depend on the temperature and pressure of deposition. A chemical vapor silicon carbide is deposited on a heated substrate at temperatures higher than 1300°C. As a result, a beta-SiC is obtained. This polytype of SiC is almost fully dense and has very fine columnar grains. Beta-SiC is then deposited on a graphite or SiC bulk material during “encapsulating” process. This technique allows the fabrication of ultra-low scatter surfaces up to 2 Å rms. Moreover, this material has outstanding mechanical properties. Its thermal characteristics are isotropic but elastic properties show some anisotropy.

CVS is a different method to deposit SiC on the surface of the bulk material.

A chemical vapor of  $\text{CH}_3\text{SiCl}_3 + \text{H}_2$  is spread on the surface where SiC is created thanks to the chemical reaction:  $\text{CH}_3\text{SiCl}_3(\text{g}) \rightarrow \text{SiC}(\text{s}) + 3 \text{HCl}(\text{g})$

This method gives different grain structures and improved properties (Fig 2(a)). Indeed, it allows fine polish, near net shape, and high reflectivity for UV and IR in vacuum.

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<sup>1</sup> Process which consists in heating a material in a powder state below its melting point to create a solid bulk of this material by diffusion and fusion of the material.

It is primordial to choose the cladding material taking into account the following properties:

- Thermal coefficient matching
- Allowable thermally induced surface error
- Machinability

Moreover, we want to keep the bending effect from the bi-metallic configuration to the minimum, consequently, to do so the differential coefficient of thermal expansion between the cladding and the mirror, the Young's modulus of the surface coating and its thickness have to be carefully chosen.

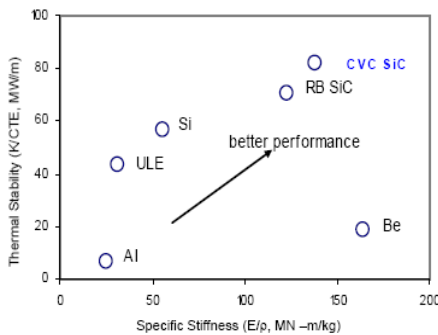
The best solution is then to use CVD-SiC as a coating material. But, because CVD –SiC is so hard, it is difficult to obtain good optical performances from this coating.

Consequently, further *polishing* procedures are required.

Indeed, with the common polishing methods, an “overpolishing” of the surface would induce “print through” effect and affect the surface shape required and “underpolishing” it would increase the polishing time and the optical performances of the surface would end up being highly limited.

A solution is to add *an ion-beam polishing* step to the fabrication of the mirror to significantly improve the rms roughness of the surface. Ion-beam polishing consists in bombarding the surface we want to polish with an ion beam –usually a beam of Ar+– and allows erosion of the surface. The resulting surface is smoother.

The surface is roughly pre-polished following the standard polishing procedures before being ion beam polished.



\*Ealey, M.A.; Wellman, J.A.; Weaver, G. “CERAFORM SiC: Roadmap to 2 Meters and 2 kg/m<sup>2</sup> Areal Density”, in *Advanced Materials for Optics and Precision Structures*, M.A. Ealey, R.A. Paquin, and T.B. Parsonage, Eds., SPIE: Bellingham, WA, 1997. RB SiC polishable to < 20 Å rms. < 3 Å rms with amorph. Si overcoat.

Figure 2- (a) Graph of thermal sensitivity as a function of stiffness

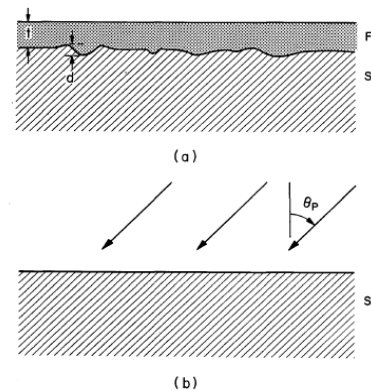


Fig. 1. Schematic diagram of the ion polishing technique. (a) The rough surface of substrate *S* is covered by a planarizing film *F*. *d* is the maximum amplitude of surface roughness. (b) Removal of the planarizing film by erosion at the planarizing angle  $\theta_p$  leaves a smooth substrate surface.

(b) Principle of Ion Beam Polishing

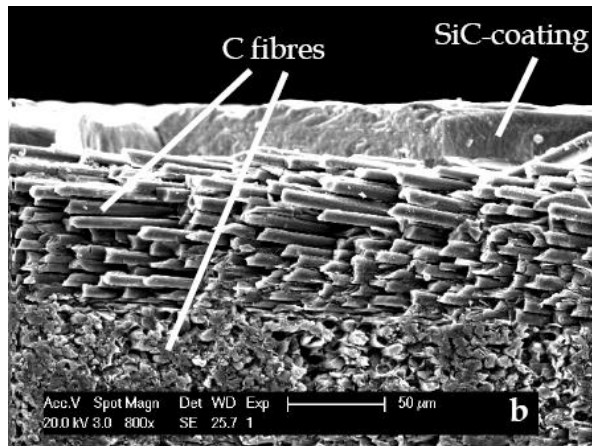


Figure 3- Cross section SEM micrograph of a specimen of carbon fiber SiC coated

Another interesting parameter of the C/SiC material is its ability to be joined using a chemical adhesive. Therefore that facilitates the design and fabrication of large mirrors or complex monolithic structures.

### III- Applications

Silicon Carbide has found a tremendous amount of applications in diverse industry areas such as semiconductors, aerospace or optics.

#### Semiconductors:

One of the most interesting properties of SiC for this application is its wide energy band gap (3-3.2 eV). This wide band gap makes it insensitive to heat and external influences and can operate at higher temperatures, radiation levels and power levels than common semiconductors. Because of its high thermal conductivity coefficient, it transfers electrons at high velocity.

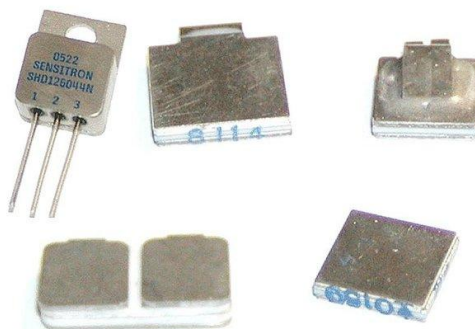


Figure 4- Silicon carbide Schottky diode from Sensitron Semiconductor

#### Aerospace applications

One more time SiC high thermal stability and stiffness are very demanded in this area and therefore, SiC is used for transfer of mechanical loads at high temperatures. For example, it is used to reinforce

the structural thermal protection systems for planetary re-entry vehicle.

Because SiC has high Young Modulus, do not oxidize, has density comparable to Aluminum but at a cheaper price, it is also used for structures reinforcement.

## Optics

As we mentioned in the introduction, SiC is becoming a very popular material for large telescopes mirrors. Indeed, its good optical properties, lightweight, high stiffness, thermal insensitivity and low cost make it a choice material for future designs and already appears in several missions. For instance, the tertiary mirror of TMT (Thirty meter Telescope) is made of SiC.

But it is mainly interesting for telescopes sent in the space such as for the current European Gaia mission. Gaia, developed by EADS-Astrium for the European Space Agency (ESA) aims to understand the structure and evolution of the galaxy and create a precise map of the Milky Way. To do so, the best optical performances are necessary but the whole structure needs to also withstand extreme working conditions. Indeed, it has to survive the transportation into the Space, but also extreme temperatures (-180°C).

SiC mirrors

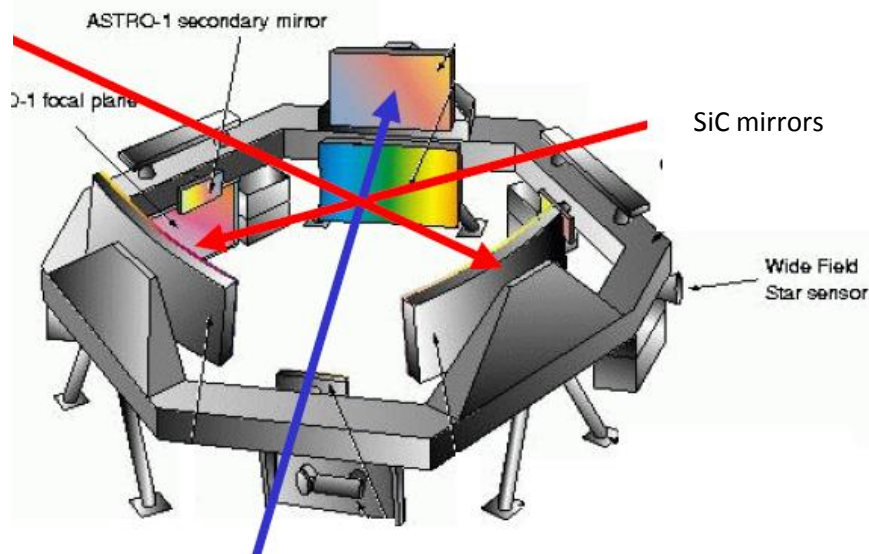


Figure 5- Schematic of GAIA's telescopes configuration

The design allows two astrometric telescopes separated by  $106^\circ$ , using  $1.4 \times 0.5$  m SiC mirrors, with a large focal plane. One additional telescope is added to the design using a medium-band photometer and a radial-velocity spectrometer. SiC mirrors are highly aspherized in this structure for off-axis performances.

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