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SILICON CARBIDE TECHNOLOGY FOR LARGE SUBMILLIMETRE SPACE BASED TELESCOPES

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RÉSUMÉ - Le carbure de silicium (SiC) présente simultanément des propriétés optiques, mécaniques et thermiques remarquables, et permet de réaliser des instruments optiques passifs ultra-stables et légers, où les miroirs et les éléments essentiels de la structure sont en carbure de silicium. Ses très bonnes propriétés thermiques (faible coefficient de dilatation thermique, homogénéité, conduction thermique comparable à celle des métaux), combinées à une capacité d'allègement pratiquement inégalée en font le matériau idéal pour les grands télescopes submillimétriques embarqués tel que FIRST.

ABSTRACT - Silicon Carbide (SiC) simultaneously provides remarkable optical, mechanical and thermal properties, and allows the realisation of low-mass, ultra-stable and fully passive optical instruments, where the optics and the major structural parts are made of silicon carbide. SiC material is most adapted to large submillimetre space based telescopes such as FIRST, since it provides excellent thermal properties (very low and homogeneous coefficient of thermal expansion, high thermal conductivity comparable to that of metals), combined with a very high lightweighting capability.

1- INTRODUCTION

Science observations in the submillimetre wavelength range (λ ~ 50 µm to 1 mm) require balloon-borne or space based telescopes because of atmospheric poor transmission. PRONAOS is an example of submillimetre balloon-borne telescope, which was built by MMS-F in 1991 for the Centre National d'Etudes Spatiales (France). Its diameter is 2-meter and the primary reflector is made of CFRP and is actively controlled during the balloon flight. The overall telescope is diffraction limited above 530 µm wavelength (WFE < 38 µm rms). FIRST and Planck are two major submillimetre programmes of the European Space Agency (ESA), which may be merged in the near future in a single programme called FIRST/Planck. Although FIRST and Planck have many common areas, their science objectives and instruments are different and their telescopes will be separated on the satellite. Both are more demanding than PRONAOS telescope, but FIRST telescope is certainly the most challenging. Therefore, the following discussion will be focussed on the case of FIRST, although most of the analysis and conclusions can be transposed for Planck case or for any submillimetre space-based large telescope

2- FIRST TELESCOPE REQUIREMENTS

FIRST (and Planck) satellite orbit is around Lagrange L_2 point, which is located on the sun-earth axis, at $1.5\ 10^6$ km distance behind the earth. The telescope temperature is expected to be as low as 60-80 K, the equilibrium temperature being obtained passively using radiative heat transfer towards cold space. The low operational temperature implies that the telescope quality on ground must be verified also at these temperatures.

Some key telescope requirements are recalled in Table 1. The telescope design goal is to reach the diffraction limit (i.e. Strehl ratio > 0.8) over the operating wavelength range. Therefore, the overall WaveFront Error (WFE) should be below $\lambda/14$ in root-mean-square value (rms), which corresponds to a WFE = 6 µm rms for a wavelength λ = 85 µm.

Primary reflector diameter	3.5 m, f/0.5
Telescope focal length	27 m
Operating wavelength	85 µm to 600 µm
Operating temperature	60 K to 100 K
Eigen frequency	> 45 Hz lateral > 60 Hz axial
Overall height	< 1.7 m
Overall mass	< 260 kg
WFE requirement	< 10 µm rms : Goal : < 6 µm rms

Table 1 : FIRST Cassegrain telescope specifications.

One can derive, from the telescope requirements, what should be the ideal material properties for FIRST [Safa 97]:

i) The material should be polishable, and allow metal coating deposition if needed. Indeed, the wavefront error specification implies a maximum surface error of about 2 µm rms for the primary reflector, which can hardly be guaranteed by grinding for a diameter 3.5 m.

ii) Its CTE should be as low as possible, isotropic, and ultra-homogeneous (large scale variations below 0.01 ppm/K). The CTE homogeneity is required because of the large variation between manufacturing and operational temperatures (ΔT > 220 K).

iii) It should preferably provide structural properties and a good thermal conductivity: in that way, the tripod can be made of the same material, and the ground tests are simplified since the alignment at room temperature will be preserved at operational temperature during cold tests or in orbit (we exclude here launch effects). The good thermal conductivity ensures that thermal gradient amplitude and effects are made negligible.

iv) It should withstand low temperatures (~ 80 K) and moderately high temperatures (~ 80 °C, for decontamination), without degradation or physical evolution.

v) Finally, it should provide a good lightweighting capability compatible with the mass requirement.

2- SICSPACE SILICON CARBIDE TECHNOLOGY

2.1- Material manufacturing

Silicon Carbide (SiC) is an emerging technology for space applications with a high growth potential. The material can be obtained by several processes, which can significantly affect either its physical properties or its cost. We shall only consider here the sintered silicon carbide manufactured by Céramiques & Composites (C&C, located at Tarbes, France) according to a well-defined and cost-efficient process. MMS and C&C have been working in close collaboration since about 5 years for developing SiC technology for space applications. The material properties and the manufacturing process of large structural or optical pieces are now fully mastered. As a consequence of this successful collaboration, both companies have recently created a commercial company, called SiCSPACE, which purpose is to efficiently promote the technology.

C&C SiC is not a new material for ground applications : The material is not toxic and has been used for many years in various industrial domains, such as fluid pumps in car or chemical industries and heat exchangers. Most often, it is used for its good mechanical and thermal properties (high strength, no fatigue, high thermal conductivity) and/or its insensitivity to hard environmental constraints (no acid or alkali attack, ability to work over a very wide temperature range (0 K to 1800 K) and to withstand thermal shocks, no humidity effects).

A considerable amount of experience and test results have been acquired by SiCSPACE, and the following data are not exhaustive, but mainly limited to FIRST purpose.

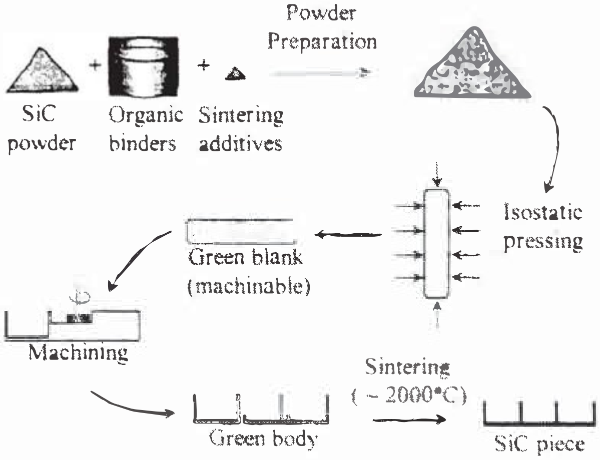

Fig. 1 : Major manufacturing steps for sintered silicon carbide.

The major manufacturing steps of a SiC blank are shown on figure 1 :

i) SiC powder preparation : Silicon carbide fine powder is mixed with organic binders and some sintering adds elements.

ii) Green body manufacturing : The powder is isostatically pressed at a high pressure.

iii) Green body machining : The green body is machined to the desired shape. For reflectors, the rear face lightweighting is performed on the green body.

iv) Sintering : The machined green body is pressureless sintered at high temperature, about 2000 °C.

The organic binders are removed during sintering process and the material is then composed of SiC over 98.5%. With the standard C&C process, the composition is controlled within 200 ppm. The pressureless sintering of SiC makes possible to reach a densification level which is over 97%. As a consequence, the ceramic exhibits a residual porosity of less than 3% and typically 2% in volume. The sintering gives an isotropic shrinkage of SiC parts. The length contraction is about 20% and C&C know-how allows to accurately master this phenomenon and therefore the size of the sintered component.

2.2- Material basic properties

Some key figures, measured by MMS, are provided in Table 2.

Material Characteristics		R.T.	110 K
Density	ρ (kg/m^3)	3160	3160
Young modulus	E (GPa)	420	420
Ultimate bending strength	σ_r (MPa)	374	405
Toughness	K_{IC} (MPa.m1/2)	2.75	2.83
Weibull modulus	m	14	14
CTE	α (ppm/K)	2	0.65
Thermal conductivity	λ (W/m/K)	190	180
Specific heat	C_p (J/kg/K)	700	135

Table 2 : Some basic physical properties of SiC, from MMS measurements.

Thermal properties

The coefficient of thermal expansion is already quite low at room temperature and drops to 0.6 ppm/K at 100 K (fig. 2). In parallel, the material thermal conductivity is very high, comparable to that of metals.

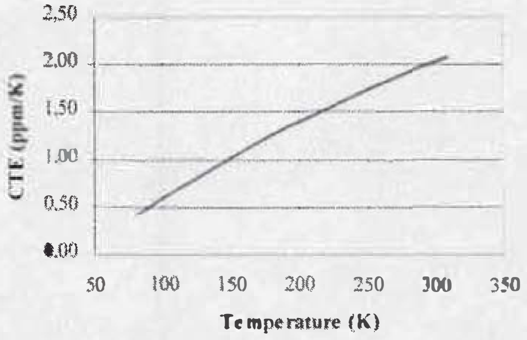

Fig. 2 : Variation of silicon carbide CTE with temperature.

The CTE homogeneity of the material is excellent (< 0.001 ppm/K) and was measured by a differential measurement technique which consists of brazing two independently manufactured pieces and measuring the sample thermal bending by optical measurements [Safa 97]. The brazing joint is very thin (~ 20 μm) and does not affect the measurement, while the temperature variation of the brazed sample is large enough (>1000°C) for providing a measurement sensitivity ΔCTE better than 0.001 ppm/K. No bending was observed.

Mechanical properties

SiC is a ceramic which presents good strength properties. Several hundred tests made by MMS and C&C experience for ground applications show that C&C SiC can safely withstand stress levels as high as 250 MPa. This allows the use of silicon carbide for building structures.

In-built stresses of *as-sintered* pieces are very low, < 0.1 MPa. No difficulty (e.g. variable distortions) was encountered for grinding or polishing of numerous pieces manufactured so far without any thermal treatment after sintering, even when a substantial amount of material was removed. No material fatigue was detected, even after 10^9 stress cycles of maximum amplitude 300 MPa.

Optical properties

The surface roughness of as sintered silicon carbide is typically Ra < 0.5 µm, which is already satisfactory for FIRST. Fine grinding allows to reduce this roughness below 0.1 µm.

C&C silicon carbide is polishable (polishing convergence as good as for glass) and the surface roughness can be made as low as 1 nm. The material can therefore be used for optics in the visible range. It can be metal-coated by using the same process than for silica glass and with similar performances.

Because of the residual porosity of the material, micro-holes are visible on a polished surface under microscope inspection. The above roughness figures should be understood « micro-holes excluded ». The micro-holes are not visible by the naked eyes since their average diameter is 2 µm. The total hole surface ratio is typically 3%, but are not seen by electromagnetic radiations of wavelength larger than the average hole size (in the same way that atomic fine structure is not seen by visible radiation). This is the case for FIRST and was confirmed by emissivity measurements made at JPL on aluminium coated samples. In fact, for reflectors working in the visible range, the surface residual porosity can be removed by depositing a thin layer of SiC CVD (non porous) prior to polishing, but this is absolutely not necessary for a submillimeter telescope and would represent an additional and useless cost.

Comparison to some other materials

	SiC	Be	Zerodur	Al
Density ρ (g/cm^3)	3.16	1.85	2.53	2.73
Young Modulus E (GPa)	420	303	91	71
CTE α (ppm/K)	2	11.4	0.05	24
Thermal conductivity λ (W/m/K)	190	180	1.6	237
Specific heat (J/K/kg)	700	1880	821	900
Ratio α/λ	0.011	0.063	0.03	0.1
Ratio E/ρ	133	164	36	26

Table 3: Material comparison at room temperature.

Table 3 provides a comparison between silicon carbide and some well-known materials. Two classical figures of merit have been added :

Thermal distortion ratio α/λ : The lower is the better. It physically reflects that thermal distortions are not only proportional to the CTE, but also to the thermal gradients, which, under given thermal environment, drop down when the thermal conductivity (λ) increases.

Specific stiffness E/ρ : The higher is this value, the better is the material lightweighting capability, for equal mechanical behaviour (e.g. equal first resonance frequency). However, a comparison only based on specific stiffness is rather theoretical, since it does not include manufacturing limitations such as the aspect ratio (rib thickness/ height). Actually, such limitations are not very constraining for SiC : an aspect ratio about 20-25 can easily be reached, and values as high as 80 with a rib thickness of 1.8 mm have been achieved.

Both figures of merit show silicon carbide advantages : except for Beryllium, which is not far from SiC, the material provides a much better lightweighting capability than others. It is also the best choice for minimising thermal distortions.

2.3- Joining techniques for manufacturing large pieces

Available facilities allow to manufacture monolithic silicon carbide pieces of dimensions up to 1 m x 1.6 m. This covers practically most of the needs and manufacturing larger monolithic pieces would require a significant industrial investment. Therefore, the cost effective and safe approach for the realisation of large pieces, such as FIRST primary reflector, is to assemble together smaller pieces, which are well within manufacturing capabilities. Several techniques can be envisaged and have been investigated :

i) Mechanical bonding, by bolting with shear pins
ii) Glass bonding
iii) Epoxy bonding
iv) High temperature brazing

Mechanical bonding is a straightforward technique which is probably the most efficient for joining structural parts. Its use for optical reflectors working in the visible is not recommended, because of potential micro-slipping between assembled parts. However, it may be envisaged for FIRST.

Glass and epoxy bonding are both mastered but have been rejected for their poor strength properties (~ 20 MPa). However, epoxy bonding (SiC/SiC or SiC/metal) is sometimes the most simple and cost efficient technique, in particular for connecting SiC to metallic parts (e.g. fittings) or gluing small pieces on a SiC structure.

Brazing technique consists of adding a material between two SiC pieces. MMS technique is a high temperature brazing which provides several remarkable properties :

- Its CTE can be matched to that of Silicon Carbide, say within 0.1 ppm/K or so.
- The brazing joint can be very thin : few µm to few tens of µm (fig. 3). But thick joints of thickness as high as 300 µm have been achieved. For thin joints, the brazing strength is comparable or better than for SiC. Numerous tests performed at liquid nitrogen temperature showed that brazing strength is practically not affected at low temperatures.
- The brazing is non-reactive, i.e. SiC is not attacked. Therefore, de-brazing is possible (for example by re-heating) without any damage of the SiC parts.

For the case of FIRST reflector, the two most interesting techniques are bolting and brazing. Brazing technique was finally selected by MMS, because it is robust, well-mastered, and it allows to avoid stress concentrations. It requires a brazing oven, of diameter ~ 4 meters.

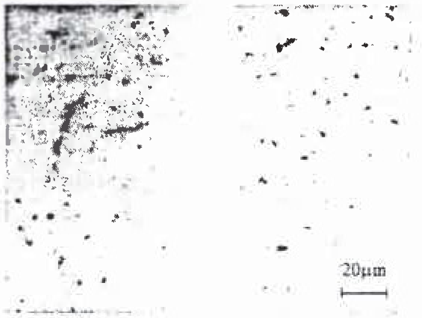

Fig. 3 : Microscope inspection of a brazing joint.

A large number of SiC pieces have been realised so far. The pieces are extremely variable in shape and size, going from C&C ring serial production (hundreds manufactured per day) to small shims of very high accuracy for optical alignments, or to medium size reflectors or blanks. We have selected here some reflector realisations, which are somehow related to FIRST telescope needs.

Fig. 4 : Polished optical reflector for visible wavelengths. Size : 720 mm x 350 mm. The reflector design is based on SPOT Zerodur steering mirror and illustrates SiC lightweighting capability. The reflector mass is 5.9 kg, more than twice lighter than the equivalent Zerodur reflector, while still providing much better mechanical performance.

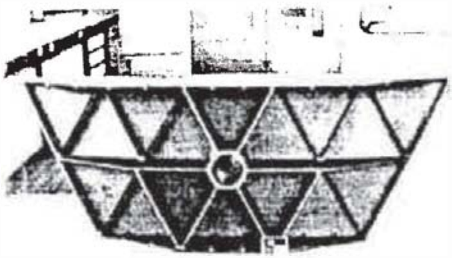

Fig. 5: Large blank manufactured under ESA contract (1200 mm x 420 mm). This breadboard demonstrates MMS C&C capability for manufacturing complex large SiC pieces.

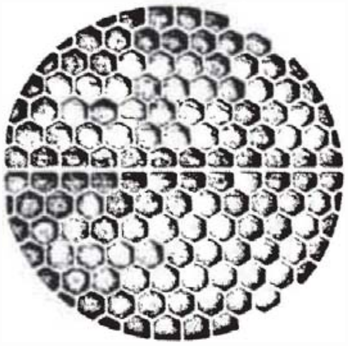

Fig. 6 : Circular blank made of two brazed pieces (rear face represented), diameter 630 mm. This blank was developed for demonstrating brazing technique.

3- FIRST « ALL-SIC » TELESCOPE

3.1- Telescope Design

We now detail the design proposed for FIRST telescope using Silicon Carbide, when the diameter was fixed to 3-meter. Going from 3 m to 3.5 m does not represent a technological step since the primary reflector is made of brazed segments. Therefore, most of the following can be transposed to the 3.5 meter telescope.

The telescope is represented on figure 7, and is composed of :

- A primary reflector (parabola), made of 12 brazed SiC segments, with pie-segmentation (as on figure 11). The brazing area height is 85 mm. The brazing joint thickness is driven by the grinding accuracy of the separate pieces and is expected to be below 50 µm. For analyses, a conservative value of 100 µm is taken. The reflector provides 3 interface points where invar inserts are fixed. There is no need for gluing the inserts : they can simply be bolted and centred on the silicon carbide. The primary reflector mass is 120 kg while the telescope mass is 154 kg.
- A secondary reflector (hyperbola), also made of SiC
- A tripod assembly, made of 3 legs connected on one hand to the primary reflector interfaces (via invar fittings) and on the other hand to a barrel holding the secondary reflector. The tripod legs and the barrel are made of SiC. This is mandatory for ensuring the secondary reflector alignment w.r.t. the primary reflector.
- isostatic mounts made of titanium
- A triangle interface mount. The triangle is made of 3 SiC tubes connected by titanium fittings

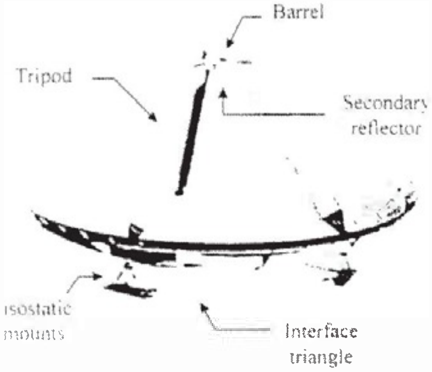

Fig. 7 : FIRST telescope elements.

ITEM	Mass (kg)
Primary reflector	120
Secondary reflector	1.8
Tripod and barrel	21.3
Mounts	7.3
Miscellaneous	3
Total	154

Table 4 : Telescope mass budget evaluation.

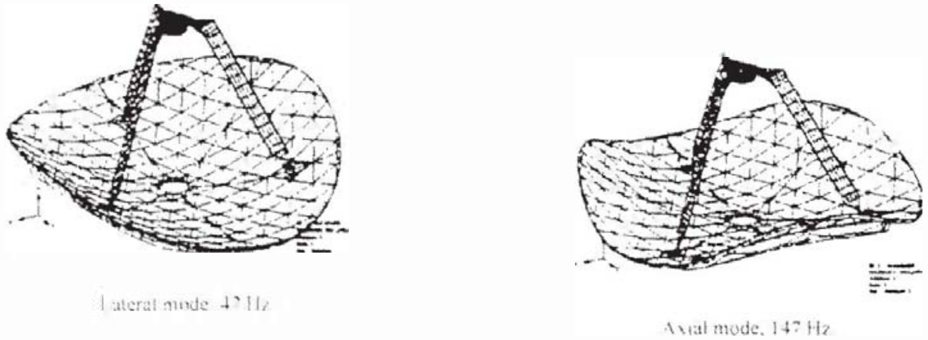
Lateral mode 47 Hz
Axial mode, 147 Hz

Fig. 8 : First modes of the telescope assembly

The primary reflector segments are brazed in one step. The reflector lightweighting was optimised for obtaining a gravity distortion below 5 µm rms, the reflector being horizontal and mounted on its bipods, while meeting the eigenfrequency requirements. Since gravity distortion can be safely predicted by a model with an accuracy better than 10% (in fact few %), it can be removed without any gravity compensation tool during tests. The telescope first eigenfrequencies are 47 Hz in lateral and 147 Hz in axial (figure 8). Both are within the specifications (Table 1). The high value of axial frequency is directly connected to gravity distortion constraint. Therefore, there is still some room for further mass reduction if one slightly relaxes the gravity distortion goal or includes gravity compensation during optical tests.

Although the 3.5 meter telescope is not yet designed, we identify here the major differences. The number of segments may be increased to 13 instead of 12, and the primary reflector mass is evaluated at less than 200 kg while the total telescope mass will be about 250 kg.

3.2- Performance analysis

A detailed performance analysis has been performed and is summarised in Table 5. As usual, root-sum-square rule is used for combining independent contributors.

Contributor	WFE (µm rms)
Reflector manufacturing	4
Assembly, Integration and test (AIT)	1.7
Cool-down distortions	-
In-orbit distortions	1.5
Telescope integration on PLM	1
TOTAL (RSS)	4.7 µm rms

Table 5 : WFE major contributors

Each contributor is split in several sub-contributors, which are not detailed here.

- Reflector manufacturing : The figure is mainly constituted by the primary reflector surface error, at room temperature, after polishing.
- AIT : The figure includes gravity distortion prediction error, wavefront measurement error in cold temperature, and reflector alignment errors at room-temperature. The 3 contributors have approximately equal weight.
- Cool-down distortions : The figure represents the additional WFE when the telescope is cooled down to 80 K. Telescope alignment is not perturbed since the design is athermal. Simulations show that the distortions due to the presence of brazing are negligible, even with a joint thickness as high as 100 µm and with a conservative CTE mismatch between the brazing and SiC of 1 ppm/K. This is due to the fact that SiC parts are homogeneous (same CTEs) and drive the overall reflector distortion (SiC part stiffness largely dominates).
- In orbit distortions : This figure includes thermal distortions in orbit and a provision for misalignments induced by the satellite launch. The telescope being athermal, the figure is in fact practically equal to launch effect provision.
- Telescope integration on the PLM : The figure represents the additional WFE which may be generated by the telescope mounting on the PayLoad Module.

The overall WFE budget is 4.7 µm rms, and is practically driven by the primary reflector polishing specification.

3.3- FIRST 1.35 meter demonstration model

For validating the whole manufacturing process proposed for FIRST primary reflector, a 1.35 meter spherical reflector is currently being manufactured by MMS/C&C in the frame of an ESTEC contract.

The demonstration model is made of 9 segments brazed together. The height of brazing areas are deliberately made representative of that of the 3.5 meter reflector. The demonstration model will be ground and polished to FIRST specifications, and then tested at cold temperature. The cold test i planned by June 98, and represents a « proof test » which will unambiguously confirm the suitability of the proposed technology for FIRST.

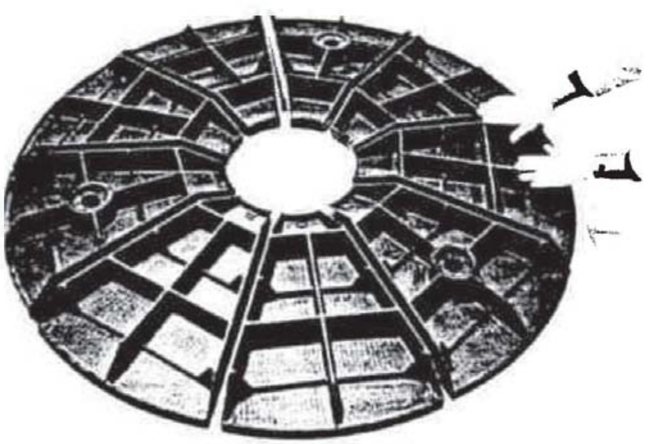

Fig. 9 : *FIRST demonstration model : diameter 1.35 m, 9 brazed segments, pie segmentation. Under manufacturing : the 9 segments are today manufactured, and the reflector will be brazed by the end of November 1997. The picture shows the rear side of the segments.*

Aknowledgments

We would like to thank ESTEC FIRST project team, MM B. Guillaume, M. von Hoegen, T. Passvogel and J.A. Steinz, for the interesting and exciting work performed so far on FIRST.

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[Safa 97] F. Safa, F. Levallois, M. Bougoin, D. Castel : "Silicon Carbide Technology for Submillimetre Space Based Telescopes", 48^{th} International Astronautical Congress, Turin, October 97.