Development of Lightweight Silicon Carbide Mirror at Cryogenic Temperatures for Infrared Imaging Surveyor (IRIS)

Takashi Onaka[1], Hideo Kaneda[2], Haruyuki Okuda[2], Hiroshi Murakami[2], Tsuguo Kohno[3], Shinji Miura[4], Ryoji Yamashiro[4], and Yoshikazu Sugiyama[4]

1. Department of Astronomy, University of Tokyo, Japan
2. Institute of Space and Astronautical Science, Japan
3. Tokyo Metropolitan Institute of Technology, Japan
4. NIKON Corporation, Japan

ABSTRACT. The development of lightweight silicon carbide mirrors for the Japanese infrared space mission, Infrared Imaging Surveyor (IRIS), is presented. The primary mirror of the IRIS has a diameter of 700mm and weighs only 8.2kg. It is made of a sandwich-type SiC material, consisting of light porous SiC core and dense chemical vapor deposition (CVD) SiC coat. The porous SiC can be easily machined and highly lightweighted structure is achievable, while the CVD SiC is good for high precision polishing. The measurements of small-scale test SiC mirror at cryogenic temperatures (~6K) show negligible deformation with temperature, indicating promising applicability of this kind of SiC for low-temperature use.

I. INTRODUCTION

The Infrared Imaging Surveyor (IRIS) is the second Japanese satellite-borne astronomical infrared telescope to be launched in 2003 (Murakami 1998), following the successful mission of the Infrared Telescope in Space (IRTS) (Murakami et al. 1996). It is a cryogenically cooled 700-mm telescope, being designed to make survey observations from near-infrared to far-infrared (2-200 μm) region with two focal-plane scientific instruments (Matsuhara 1998, Kawada 1998). It will also have a focal-plane star sensor in order to reconstruct the telescope pointing. The telescope temperature is designed to stay stable at about 6K to suppress thermal background and nearly diffraction-limited performance in the near-infrared region is required for the cooled telescope system to achieve faint object detection. The telescope system has to meet the severe weight constraint and launching conditions as well. Taking account of these constraints, we have decided to employ silicon carbide (SiC) mirrors for the IRIS telescope. SiC can be polished to high precision and has good thermal conductivity. It can also be lightweighted largely because of the large Young's modulus. In this report, we present the development status of the SiC mirrors for the IRIS and particularly the latest results of experiment of a test SiC mirror at cryogenic temperatures. Details of the IRIS telescope system is described in Onaka et al. (1998).

2. MIRROR DESIGN

Various kinds of silicon carbide mirrors have been developed in recent years, including reaction-bonded SiC (e.g., Tobin et al. 1995), hot-pressed SiC (Shi and Ezis 1995), and silicide SiC (Robb et al. 1995a). The performance at cryogenic temperatures has also been reported in some cases, indicating very little change in the figure of the mirror for the temperature range of 300 to 4K (Robb et al. 1995b). Silicon carbide we have been developing for the IRIS telescope is a kind of sandwich-type, which consists of porous core and dense CVD (chemical vapor deposition) coat. The material properties of each SiC at room temperature are summarized in Table 1 together with those of beryllium and fused quartz for comparison. In Table 1 we list slightly different numbers for the specific heat of SiC from those listed in Onaka et al. (1998).

Table 1. Material properties at room temperature

Properties	*Unit*	*Porous SiC*	*CVD SiC*	*Beryllium*	*Fused quartz*
Young's modulus	GPa	147	490	287	74.5
Density	g cm^{-3}	1.85	3.21	1.85	2.19
CTE	10^{-6} K^{-1}	4.4	4.5	11.3	0.5
Thermal conductivity	W m^{-1} K^{-1}	31	67	216	1.4
Specific heat	J kg^{-1} K^{-1}	920	710	1925	750

The porous core SiC has a very low density, almost the same as beryllium. It can also easily be machined, and thus highly lightweighted structure can be fabricated. On the other hand, the CVD SiC is dense and strong, and can be polished to very low surface roughness. The combination of these properties of the present sandwich-type SiC enables the fabrication of lightweight mirror with high precision.

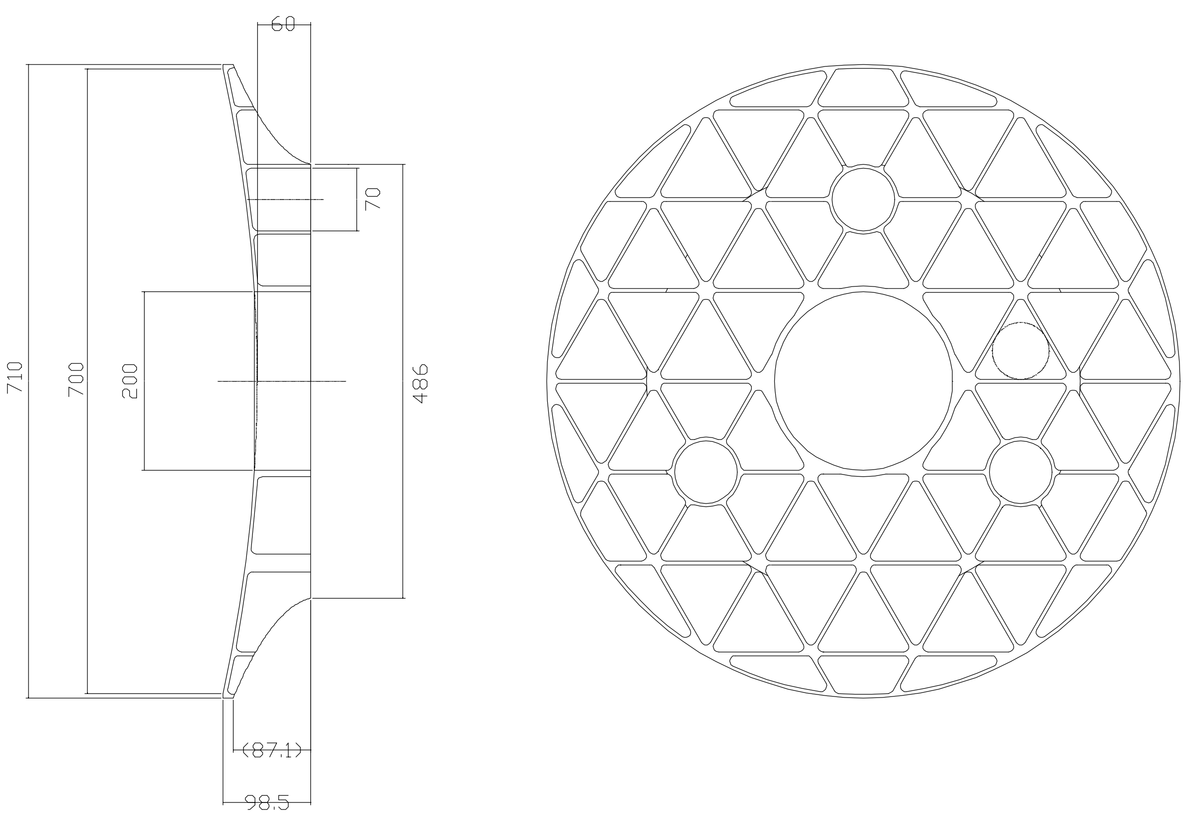

Figure 1. Design of the IRIS primary mirror. The units are in mm.

With these characteristics of the material, the primary mirror of the IRIS has been designed as shown in Figure 1. The focal length of the primary mirror is designed to be about 800mm, providing a quite fast (f/1.14) beam in order to reduce the telescope length (Onaka et al. 1998). The porous core SiC has a thickness of 3mm, making the rear triangular structure and front surface. The thickness of the CVD SiC is set as 0.5mm for the both sides. The sandwich-type SiC of this combination gives an average density of about 2.2 g cm^{-3} and the total expected weight of the 710-mm diameter mirror is 8.2 kg. The thickness of the CVD coat and the porous core is fixed mainly by the allowance in the machining of the core structure, but not by the requirement of strength of the structure. The CVD SiC has a quite large Young's modulus. If the machining process is improved, further reduction in the density and thus in the weight will be expected.

3. MEASUREMENTS AT CRYOGENIC TEMPERATURES

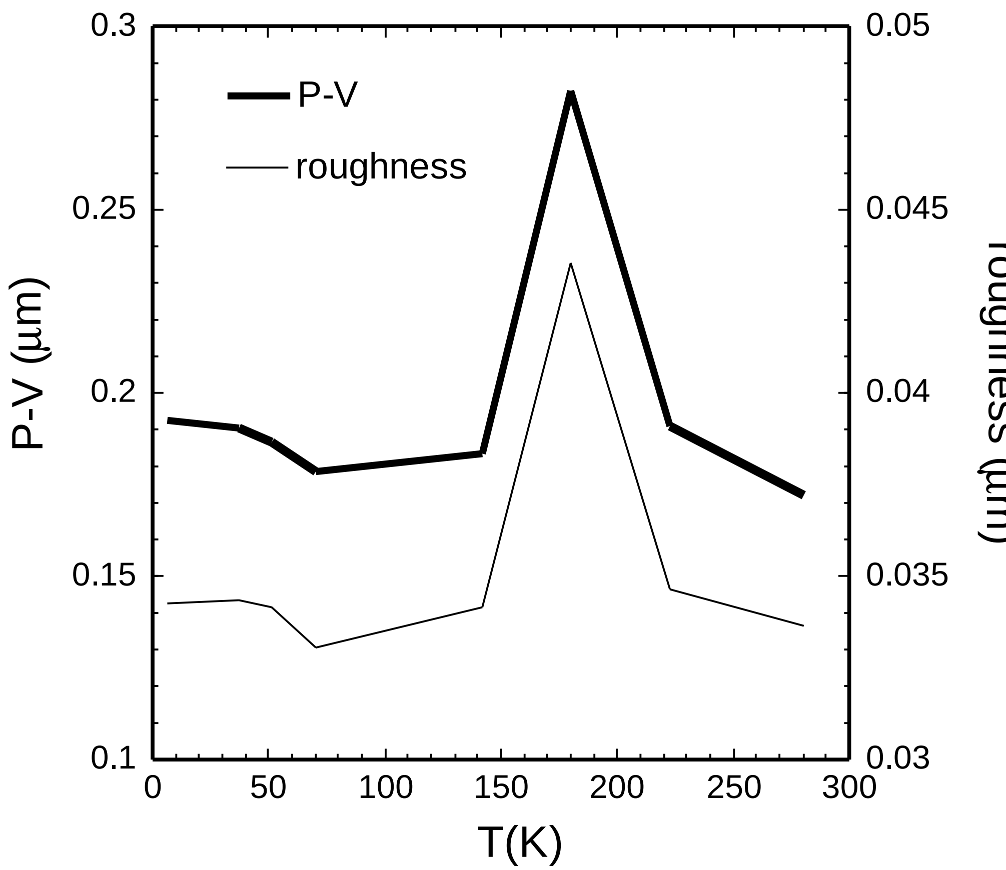

Figure 2. Plot of the SiC mirror figure in the peak-to-valley (thick line) and surface roughness (thin line) against the temperature. They do not change appreciably from 280K to 6K with a slight increase around 180K.

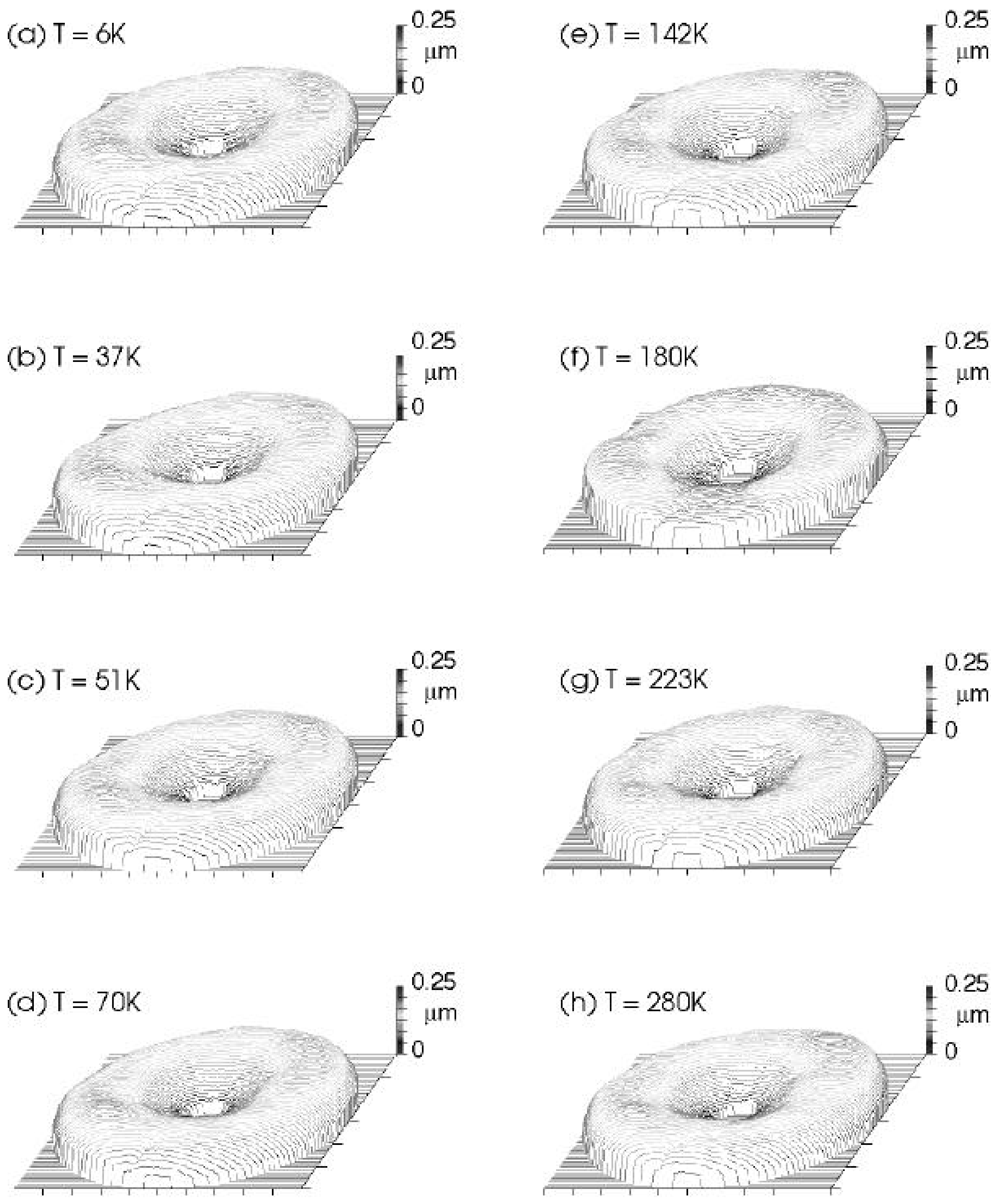

Figure 3. The change of the test SiC mirror (160mm in diameter) figure with temperatures (a: 6K, b: 37K, c: 51K, d: 70K, e: 142K, f: 180K, g: 223K, h: 280K). All figures are in the same scale.

There may be a slight difference in the CTE between the porous and CVD SiC, which could result in deformation of the mirror figure at low temperatures. In order to test the cryogenic performance of the sandwich-type SiC mirror, a test spherical mirror of 160 mm in diameter of a similar structure to the primary mirror was fabricated. The change in the surface figure of the test mirror was measured by an interferometer for the temperature range of 280K to 6K. The test mirror was placed in a liquid helium cryostat and was hung by a stainless steel belt in order not to have extra stress from the support. Heat straps were attached to the SiC mirror directly from the liquid helium tank. The temperatures of the cold plate and the mirror were monitored separately. The difference in the temperatures was quite small, indicating the good thermal conductivity of SiC even at low temperatures. The lowest temperature reached was 6K, which was about the expected operating temperature of the IRIS telescope (Murakami 1998).

The peak-to-valley value of the surface figure relative to the ideal spherical surface and the rms surface roughness are plotted against the temperature in Figure 2. The change of the surface figure with temperature is shown in Figure 3. All the measurements were made while the mirror was being warmed up from 6K because the cooling was so rapid and the stable measurements were not possible during the cooling down. The present measurements have also confirmed that the surface figure at room temperature stayed the same before and after the cooling.

Figures 2 and 3 indicate that the deformation due to the change of temperature is quite small and less than the measurement errors. There may be a possible transient deformation around 180K. However, it is still about 0.01 μm (rms) and disappears at lower temperatures. In the error budget of the IRIS telescope design, we allocate about 0.06 μm (rms) to the wavefront error of the primary mirror, including the deformation at low temperatures. The present result indicates that this goal can be achieved with a fair margin. It also clearly demonstrates the promising applicability of this kind of SiC material to cooled telescope mirrors.

4. CURRENT STATUS OF THE IRIS MIRROR

Prior to the fabrication of porous SiC core mirror, a mirror of the same size with graphite core has been made in order to confirm the machining process. The graphite core mirror was coated with CVD SiC and is being polished to confirm the polishing process. Figure 4 shows the graphite-core-CVD-SiC-coat mirror blank of 710-mm diameter before polishing. The first blank of the SiC core has been fabricated and now is being machined. It will be coated with CVD SiC after machining. Then it will be partially polished and assembled in the prototype-model (PM) telescope. The PM telescope assembly will be tested against the launching conditions and at liquid helium temperatures. The flight-model mirror will be finished about a year from now and will be tested at low temperatures in a facility built at ISAS. The whole assembly of the flight-model telescope will also be tested in the same facility.

5. CONCLUSIONS

We have been developing sandwich-type SiC mirrors for space-borne cooled telescope application. They are still in the developing stage, but the results so far obtained demonstrate promising characteristics of this kind of SiC in the fabrication of lightweight high-precision mirrors for cooled telescopes. The current mirror has an areal density of 20.7 kg m^{-2}. Improved machining processes can further reduce this number. The launching vehicle to be used for the IRIS will have quite severe vibration conditions, which require some

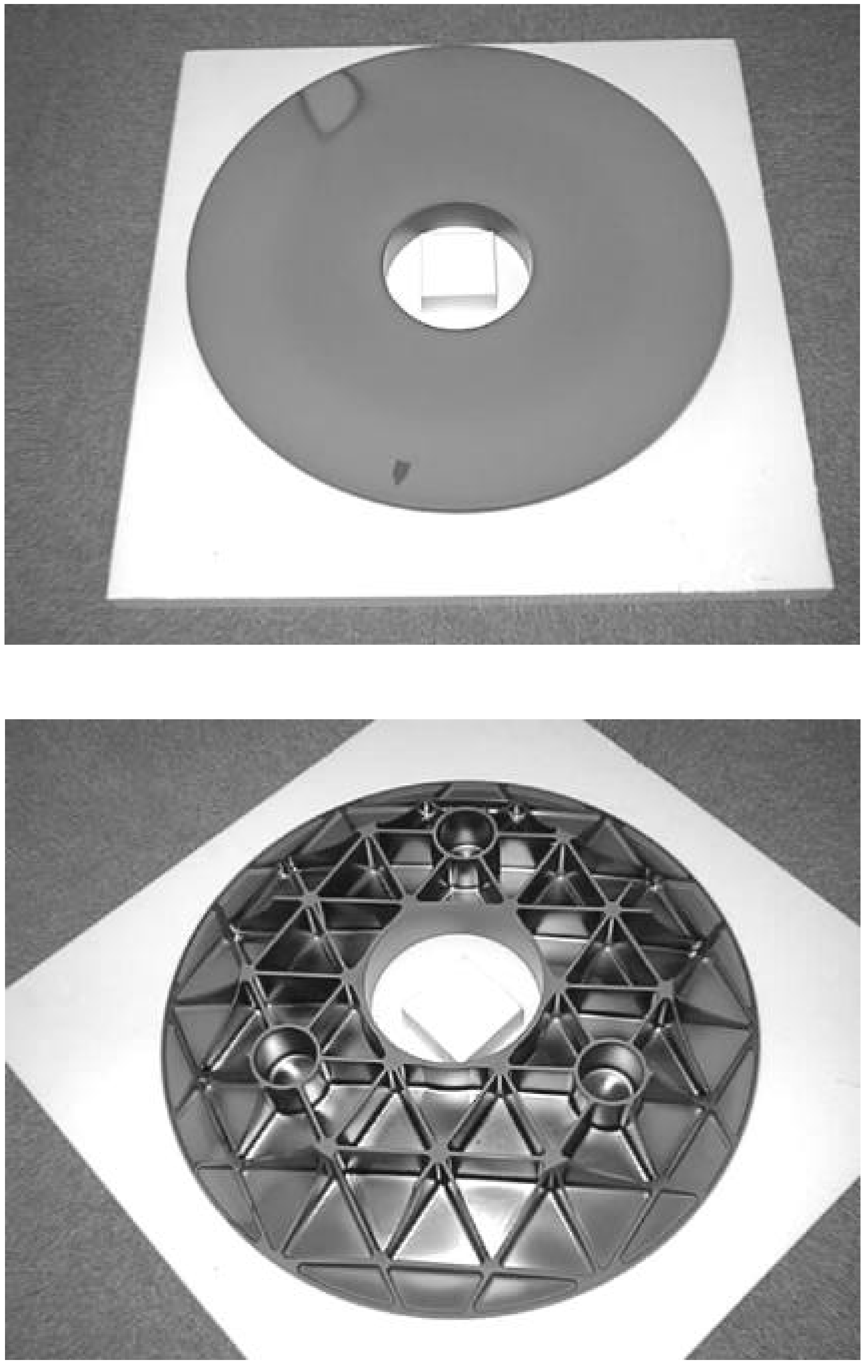

Figure 4. Photos of the graphite-core SiC-CVD-coat blank of 710 mm in diameter before polishing. A spot seen in the upper photo is a minor problem of the CVD coat on the surface and disappeared after polishing. An arrow in the photo is a position indicator. The lower photo shows the rear side structure of the mirror.

strength in the support structure. Designs of the support structure for less severe launching conditions may allow further reduction in the weight. Currently the available size of this SiC blank is limited to less than 1m because of the size of the furnaces, but there seem no serious technical difficulties to increase it to over 1m. Further developments and investigations are badly needed, but this type of SiC shows potential applicability to large lightweight mirrors in cooled space telescopes.

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