High-Precision CTE Measurement of SiC-100 for Cryogenic Space Telescopes

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ABSTRACT. We present the results of high-precision measurements of the thermal expansion of sintered SiC, SiC-100, intended for use in cryogenic space telescopes, in which minimization of thermal deformation of the mirror is critical, and precise information of the thermal expansion is needed for the telescope design. The temperature range of the measurements extends from room temperature down to ∼10 K. Three samples, Nos. 1, 2, and 3, were manufactured from blocks of SiC produced in different lots. The thermal expansion of the samples was measured with a cryogenic dilatometer, consisting of a laser interferometer, a cryostat, and a mechanical cooler. The typical thermal expansion curve is presented using an eighth-order polynomial of the temperature. For the three samples, the coefficients of thermal expansion (CTE), α1, α2, and α3, were derived for temperatures between 293 and 10 K. The average and the dispersion (1 σ rms) of these three CTEs are 0.816 × 10−6 and 0.002 × 10−6 K−1, respectively. No significant difference was detected in the CTE of the three samples from the different lots. Neither inhomogeneity nor anisotropy of the CTE was observed. Based on the CTE dispersion obtained, we performed a finite-element method (FEM) analysis of the thermal deformation of a 3.5 m diameter cryogenic mirror made of six SiC-100 segments. It was shown that the present CTE measurement has an accuracy that is sufficient for the design of the 3.5 m cryogenic infrared telescope mission SPICA (Space Infrared Telescope for Cosmology and Astrophysics).

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1. INTRODUCTION

Development of light-weight cryogenic mirrors is a key technology for infrared astronomical space telescope missions, which have great advantages, being free from the turbulence, thermal background, and absorption caused by the atmosphere. The technology supporting light-weight mirrors is essential to bringing large mirrors into space, which enable high sensitivity and a high spatial resolution. The infrared sensitivity of a space telescope is vastly improved by the reduction of the thermal background by cooling the telescope to cryogenic temperatures. Thus, it is essential that infrared space telescopes have cooled light-weight mirrors with sufficient optical quality.

Silicon carbide (SiC) is one of the most promising materials for space telescopes, because of its high ratio of stiffness to density. The Japanese space mission Akari, designed to carry out infrared astronomy, carries a 68.5 cm aperture telescope whose mirrors are made of multilayered SiC consisting of a porous SiC core and a chemical vapor deposited SiC coating (Murakami 2004; Kaneda et al. 2005). The entire Akari telescope system is cooled down to 6 K by helium gas vaporizing from liquid helium. Akari was launched in 2006 February, and the telescope system has been confirmed to perform as expected from prelaunch ground tests (Kaneda et al. 2007). The Herschel Space Observatory, a submillimeter satellite mission by the European Space Agency (Pilbratt 2004), employs mirrors of sintered SiC (SiC-100) provided by Boootech Industries and EADS-Astrium (Breysse et al. 2004). The 3.5 m diameter primary mirror of the Herschel space telescope is made of 12 segments brazed together. The Herschel Space Observatory will be launched in 2008 to make observations in 60–670 μm, while the telescope will be kept to ∼80 K by passive cooling. SiC-100 is one of the most frequently used SiC’s for space optics. It has been used for the telescopes of the Aeolus, Gaia, ROCSAT, and other missions (Breysse et al. 2004 and references therein).

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is the next-generation mission for infrared astronomy, planned by the Japan Aerospace Exploration Agency (Nakagawa et al. 2004; Onaka et al. 2005). The SPICA telescope is required to have a 3.5 m diameter aperture and will be cooled down to 4.5 K by a combination of radiative cooling and mechanical coolers (Sugita et al. 2006). SPICA is
planned to be launched in the middle of the 2010s and will execute infrared observations in 5–200 μm. SiC-100 is one of the promising candidate materials for the mirrors and structures of the SPICA telescope, while carbon-fiber–reinforced silicon carbide is another candidate now being investigated (Ozaki et al. 2004; Enya et al. 2004, 2007). Monolithic primary mirrors can be manufactured by joint-segment technology, similar to that used for the primary mirror of the Herschel telescope. However, the requirement for the surface figure accuracy of the SPICA primary mirror is better than 0.06 μm rms. This requirement is ~20 times more rigorous than the Herschel Space Observatory, because of the difference in the targeted wavelength ranges.

In the development of cryogenic space telescopes, it is important to suppress the thermal deformation of the mirror caused by cooling in order to satisfy the requirement for the surface figure accuracy (Kaneda et al. 2003, 2005). Therefore, the study of the coefficients of thermal expansion (CTE) of the material used for the mirror is important. The CTE data of the mirror material are indispensable for the design of cryogenic space telescopes, because the actual telescope mirror needs to accommodate complicated support structures consisting of materials that differ from that of the mirror. If the CTE measurement of test pieces of the mirror material has sufficient accuracy, this will enable us to predict the thermal deformation of a segmented mirror caused by the dispersion in the CTE of each segment. The most direct and highly sensitive test of thermal deformation is an interferometer measurement of the actual mirror at cold temperatures. The CTE data are useful to interpret the result of direct measurements of the mirror and to investigate the origin of the observed deformation.

However, measurements of the CTE of SiC and its dispersion have not yet been performed with sufficient accuracy and for a wide temperature range. In particular, few data are available at temperatures lower than 77 K, which can be realized by only liquid-nitrogen cooling. Prior to this work, available CTE data on SiC-100 were limited to temperatures higher than ~77 K (Y. Toulemont 2005, private communication). Pepi & Altshuler (1995) presented CTE data for reaction-bonded optical-grade (RBO) SiC down to 4 K, based on measurements with samples made from one block of the RBO SiC. The CTE of the new-technology SiC (NT-SiC), developed to have high-strength reaction-sintered SiC, has been reported down to 20 K for one sample (Suyama et al. 2005).

In this work, we present the results of high-precision CTE measurements of SiC-100 down to cryogenic temperatures for samples from three different lots. We set two major goals for the present work: one is to provide the typical CTE of SiC-100 for the development of the SPICA telescope, and the other is to estimate the thermal deformation of segmented mirrors from the measured CTEs.

2. EXPERIMENT

2.1. Sample

Figure 1 shows three samples (Nos. 1, 2, and 3) of SiC-100 measured in this work. All of the samples were manufactured by Boostec Industries and EADS-Astrium (Breysse et al. 2004). Each of the samples was extracted from blocks of SiC produced in different lots. The locations of each sample in the SiC blocks are arbitrary. The samples are rectangular parallelepipeds, with the dimensions of 20.00±0.05 × 20.00±0.05 × 6.00±0.1 mm. Flatness, parallelism, and roughness of the 20.00 × 6.00 mm surfaces are important for the measurement of this work. The flatness of these surfaces is ≤2/100 rms, where λ is the wavelength of the HeNe laser, 632.8 nm. The parallelism of the opposing 20.00 × 6.00 mm surfaces is less than 2"., while the parallelism of the opposing 20.00 × 20.00 mm surfaces is less than 1.0". All of the 20.00 × 6.00 mm surfaces are polished to an optical grade, and the surface roughness finally achieved is less than 3 nm rms. Owing to the polish of the surface, laser light directly reflected by the sample was used for the measurement. As a result, the measurement was free from uncertainty due to any additional mirrors or coating, which would occur if directly reflected light could not be used.

2.2. Measurement

The measurement of thermal expansion was carried out with a laser interferometric dilatometer system for low temperatures developed at the National Metrology Institute of Japan, Advanced Industrial Science and Technology division (Yamada & Okaji 2000, hereafter Paper I; Okaji & Yamada 1997; Okaji et al. 1997). The system consists of a cryostat, a cryogenic mechanical Gifford-McMahon (G-M) cycle refrigerator (V204SC, by Daikin Industries, Ltd.), and an interferometer utilizing acousto-optical modulators and the stabilized HeNe laser system (05STP905, by Melles Griot, Inc.). The cooling is performed with the refrigerator alone, and no cryogen is needed. The minimum temperature achieved in this work is about 10 K. The space around the cold stage of the cryostat, containing the installed sample, is filled with 130 Pa helium gas and sealed off at room temperature before cooling, to ensure thermal uniformity. The configuration of the whole cryostat and the sample installation into the cold stage of the cryostat are respectively shown in Figures 1 and 2 of Paper I. The change in the length of the sample, ΔL, is measured with a double-path–type laser interferometer in the optical heterodyne method, with a digital lock-in amplifier (model SR-850) from Stanford Research Systems, Inc. Details of this system are given in Paper I.

We made a total of six measurements of the CTEs of SiC-100. In each measurement, the sample was initially cooled down to ~10 K, and the proportional integral derivative (PID) temperature control was then applied. After the temperature had been stabilized, the temperature and the change in sample length
were measured. The temperature stability during the measurement was less than 0.02 K hr$^{-1}$. This process was repeated for approximately 16 temperatures at roughly equal intervals up to room temperature. One data set of temperature versus $\Delta L$ was obtained for one cooling cycle. To compensate for the systematic uncertainty, each measurement was repeated by rotating the sample by 90°, as described in Figure 2 of Paper I. We measured CTEs in two orthogonal directions (A and B directions, as shown in Fig. 1) for each sample. The directions A and B were arbitrary chosen.

3. RESULTS AND DISCUSSION
3.1. Typical Thermal Expansion

The results of the measurement of thermal expansion are presented in Figure 2. A fit with an eighth-order polynomial is applied to each of the six data sets, and the thermal expansion (contraction) $\Delta L/L$ is set at zero at 293 K for each of the six curves. The six data sets are plotted in Figure 2a. We present the curve derived from the fit of all six data sets, giving the typical thermal contraction of SiC-100, shown by the solid line. The coefficients of the eighth-order polynomial, $\Delta L/L = \sum_{i=0}^{8} a_iT^i$, are presented in Table 1. Figure 2b shows the residual dispersion of the data after subtracting the fitted curve. The shape of the curve in Figure 2a is roughly compatible with those of the RBO SiC (Pepi & Al'tshuler 1995) and NT-SiC (Suyama et al. 2005), although the slightly negative CTEs seen in the RBO SiC and NT-SiC observed at temperatures below 50 K are not seen in the present measurements for SiC-100. Because of the uncertainties in the other measurements, it is difficult to further investigate the origins of the differences at present.

For each of the six curves, the average $\Delta L/L$ per temperature between 293 and 10 K is derived and summarized in Table 2. The average of the six values and their dispersion (1 $\sigma$) are $0.816 \times 10^{-6}$ and $0.005 \times 10^{-6}$ K$^{-1}$, respectively. The dispersion is smaller than the previous upper limit of $0.01 \times 10^{-6}$ K$^{-1}$ in Paper I, obtained with high-purity single-crystal silicon, indicating that the present measurements have reached the limit set by the instrument.

Pepi & Al'tshuler (1995) have shown a 1 $\sigma$ dispersion of $0.04 \times 10^{-6}$ K$^{-1}$ for their measurements. Karlmann et al. (2006) showed the repeatability of the CTE measurement to be $0.004 \times 10^{-6}$ K$^{-1}$ from 35 to 305 K, using single-crystal silicon in the interferometer-based cryogenic dilatometer. Compared with Karlmann et al. (2006), our measurements reached lower temperatures. Thus, the present dispersion is concluded.
to be well below the measurement uncertainty, and we do not detect any significant variations in the CTEs of the present six measurements. Nor do we detect any differences in the CTEs in different directions of the same sample, or in the samples extracted from different lots. Thus, the SiC-100 we have measured is homogeneous and isotropic within the present measurement uncertainty. Finally, we average two values of $\alpha$ in directions A and B for each of three samples, to obtain $(\bar{\alpha}_1, \bar{\alpha}_2, \bar{\alpha}_3) = (0.8145, 0.8160, 0.8185) \times 10^{-6} \text{ K}^{-1}$. The average and the dispersion (1 $\sigma$ rms) of these three CTEs are $0.816 \times 10^{-6}$ and $0.002 \times 10^{-6} \text{ K}^{-1}$, respectively.

### 3.2. Alternative Measurements of the Dispersion of CTE

Differential tests of the CTE dispersion is another strong tool to investigate variations in the CTE. The quite small dispersion in the CTEs of SiC-100 has been confirmed by a systematic check made by EADS-Astrium in the manufacturing process of the mirror segments of the *Herschel Space Observatory*. All 12 segments of the *Herschel* primary mirror came from different SiC powder batches. The measurement of the bending deflection was made for two pairs of thin, brazed SiC samples coming from different batches of SiC. The samples were placed in a vacuum chamber, and the thermal deformation of the samples’ surfaces was measured with an interferometer between room temperature and 150 K. The deformation data are directly linked to the curvature of the bending deflection and the difference of the CTE between the two samples.

In order to validate the homogeneity of the SiC material, two kinds of verification were performed on the material. The first was a test of the homogeneity inside a spare segment. For this test, samples were cut out from a spare sintered segment at several locations (along radial, tangent, and thickness directions). The second test was of homogeneity between samples belonging to different flight segments. For this test, as it was not possible to take samples from the flight segments after sintering, the samples were cut out from different segments at their “green body” stage, before the sintering of the segments. Those samples were taken from arbitrary locations of the segments (different orientations and locations were therefore present in the test samples). Those samples were made similar to

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**Table 1**

| Coefficient | Value     |
|-------------|-----------|
| $a_0$       | +2.43165 $\times 10^{-1}$ |
| $a_1$       | -9.25541 $\times 10^{-2}$ |
| $a_2$       | +7.38688 $\times 10^{-4}$ |
| $a_3$       | +2.44225 $\times 10^{-5}$ |
| $a_4$       | +5.68470 $\times 10^{-7}$ |
| $a_5$       | +5.94436 $\times 10^{-9}$ |
| $a_6$       | -4.03400 $\times 10^{-11}$ |
| $a_7$       | +8.70017 $\times 10^{-14}$ |
| $a_8$       | -6.64445 $\times 10^{-17}$ |

*Note.—Coefficients of the eighth-order polynomial $\Delta L/L = \sum_{i=0}^{8} a_i T^i$ represent the typical thermal expansion of SiC-100 below 300 K.*

**Table 2**

| Sample | Direction | $\bar{\alpha}$ ($\times 10^{-6}$ K$^{-1}$) |
|--------|-----------|------------------------------------------|
| 1      | A         | 0.820                                     |
| 1      | B         | 0.809                                     |
| 2      | A         | 0.821                                     |
| 2      | B         | 0.811                                     |
| 3      | A         | 0.815                                     |
| 3      | B         | 0.822                                     |

* Nos. 1, 2, and 3 correspond to the sample number shown in Fig. 1.

A and B correspond to the direction of the sample for the measurement shown in Fig. 1.

$\Delta L/L$ is between 293 and 10 K.
Fig. 3.—Model for the FEM analysis. (a) Three-dimensional view of the model of the whole mirror seen from the reflective side. (b) The same model, but seen from the back side of the mirror. Three triangles on the rib indicate points for constraints. All three points were constrained in the three lines shown by the arrows. The labels s1–s6 are for the identification of the segments (see also Fig. 4). Panels (c) and (d) show a three-dimensional view and the geometry of one segment, respectively.
the segments themselves by taking care to sinter them in the same run as the associated segments. In this way, it was possible to reproduce the differential CTE characteristics. In the telescope manufacturing process, 12 samples of the 12 segments were brazed on the reference samples and tested at 150 K. The results indicate the dispersion (1 \( \sigma \) rms) to be smaller than 0.0025 \times 10^{-6} K^{-1}.

The agreement of the dispersion of the CTE derived by two different methods signifies that both of the measurements are reliable and that the uniformity of the CTE of the SiC-100 is well confirmed. The direct measurement of the CTE of this work and the differential measurement are complementary: the direct measurement provides absolute CTE data down to 10 K with high accuracy, which is indispensable to the design of a space telescope, including the surrounding structures, while the differential test checks the uniformity of the CTE for a large number of the samples.

### 3.3. Simulation of the Mirror Deformation

It is beneficial to relate the accuracy of the CTE measurement to the corresponding thermal deformation of the mirror. In this section, the thermal deformation of the segmented mirror is estimated on the basis of the measured dispersion of the CTE values. To examine this issue, we perform a case study by using a simple model in a finite-element-method (FEM) analysis. All of the simulated thermal deformation is derived for the case of cooling down from 293 to 10 K. Figure 3 shows the model used in the FEM analysis. One mirror with a center hole is constructed from six segments with a rib structure as shown in Figures 3a and 3b for a light-weight mirror design. In this model, it was assumed that the mirror surface is flat, for simplicity. Figures 3c and 3d show a three-dimensional view and the geometry of one segment, respectively. The diameter of the whole mirror is 3.5 m, equal to the design diameter of the primary mirror of the \( \text{SPICA} \) telescope and to the \( \text{Herschel Space Observatory} \). The thickness of the rib structure and the mirror surface is 3 mm. The Young modulus and the Poisson ratio of SiC-100 at room temperature are reported to be 420 GPa and 0.17, respectively (Breysse et al. 2004; Y. Toulemont 2005, private communication). We use these values in the simulation of the thermal deformation, since the temperature dependence of these quantities is usually small and is not available at present. In the FEM analysis, the rotationally symmetric axis of the mirror is set along the \( z \)-axis of the Cartesian coordinates. The constraints of the model are shown in Figure 3b: three points on the rib of the mirror, indicated by triangles, are constrained on the lines in the \((x\,-y)\)-plane, as shown by the arrows. These points are free along the radial direction within the constraint lines. Therefore, these constraints do not cause inner stress in the mirror in the simulation of the cooling and thermal deformation.

The results of the simulation are presented in Figure 4. Figure 4a shows the thermal deformation toward the \( z \)-direction of the mirror surface, obtained from the FEM analysis, in which \( \tilde{\alpha}_1 \), \( \tilde{\alpha}_2 \), and \( \tilde{\alpha}_3 \) are given for segments (s5, s6), (s1, s2), and (s3, s4), respectively (case 1). Figure 4b shows the simulated \( z \)-direction deformation, in which \( \tilde{\alpha}_1 \), \( \tilde{\alpha}_2 \), and \( \tilde{\alpha}_3 \) were given for segments (s3, s6), (s2, s5), and (s1, s4), respectively (case 2). Cases 1 and 2 are configurations in which the two segments having the same CTE are represented as being adjoined and in opposite positions, respectively. As a result, the configuration of case 1 corresponds to a mirror that consists of three segments...
having $\alpha_1$, $\alpha_2$, and $\alpha_3$, while the configuration of case 2 corresponds to a mirror having a CTE distribution that is $180^\circ$ rotationally symmetric. Both Figures 4a and 4b show the surface after tilt correction. For cases 1 and 2, 0.032 and 0.040 $\mu$m ($1 \mu$m rms), respectively, are obtained as the surface deformations after performing tilt correction. Since the requirement for the surface figure accuracy of SPICA is 0.06 $\mu$m rms, the FEM analysis indicates that the thermal deformation estimate based on the measured CTE dispersion among the segments is sufficiently small for the SPICA telescope.

The temperature expected for SPICA is 4.5 K, while the lowest temperature of the CTE measurement in this work is $\sim 10$ K. However, the thermal contraction between 10 and 4.5 K is negligible and does not affect the mirror deformation at all. It is shown that the accuracy of the CTE measurement achieved in the present study is sufficient to investigate the thermal deformation for a surface figure error of less than 0.06 $\mu$m for a segmented SiC mirror that is 3.5 m in diameter.

4. CONCLUSION

In this work, we perform high-precision measurements of the thermal expansion of sintered SiC, SiC-100, for use in cryogenic space-based telescopes. Three samples of SiC-100 from different lots are measured. The temperature measurements range from room temperature to $\sim 10$ K. The following results are obtained.

1. The typical thermal expansion of SiC-100 is given in the form of $\Delta L/L = \sum_{i=0}^{8} a_i T^i$. The coefficients are shown in Table 1.
2. The CTEs were measured from three samples taken in two orthogonal directions. The average and the dispersion (1 $\sigma$) of these six values between 293 and 10 K are $0.816 \times 10^{-6}$ and $0.005 \times 10^{-6}$ K$^{-1}$, respectively. The dispersion is well below the present measurement uncertainty.
3. The homogeneity and anisotropy of the CTE of SiC-100 has been confirmed within the present measurement accuracy.
4. The small dispersion of the absolute CTE that we obtained is compatible with the results of the differential CTE measurements using brazed samples made at EADS-Astrium.
5. For the three samples, nominal CTEs $\alpha_1$, $\alpha_2$, and $\alpha_3$ were derived for temperatures between 293 and 10 K by averaging two CTE data in two directions for each sample. Their dispersion (1 $\sigma$) was $0.002 \times 10^{-6}$ K$^{-1}$.
6. The thermal deformation of a segmented mirror is estimated by FEM analysis, using $\alpha_1$, $\alpha_2$, and $\alpha_3$. The results indicate that the present measured dispersion is sufficiently small and is well below the SPICA requirements for thermal deformation of the mirror, 0.06 $\mu$m rms.

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