MULTIFUNCTIONAL SPACEBORNE BLACKBODY SYSTEM FOR ON-BOARD CALIBRATION OF IMAGE SENSORS

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ABSTRACT

Multifunctional spaceborne blackbody system was developed to improve the accuracy in estimating the temperature of the blackbody surface by integrating with micro-heaters, micro-coolers, and micro-temperature sensors for on-board calibration of image sensors in space applications. Consequently, a lightweight, low power consumption, high accuracy blackbody system has been realized. The temperature uniformity within 0.01°C was achieved so that the exact representative temperature of the blackbody surface could be provided for the wide-range temperature calibration of image sensors.

INTRODUCTION

The spaceborne image sensors require periodic calibrations using a blackbody system to correct non-uniform output characteristics due to the repeated on-off operations. However, currently available spaceborne blackbody systems are not accurate enough to perform the precise calibration of image sensors because the conventional temperature sensors could not provide the exact representative temperature [1-6]. In addition, the existing blackbody system is heavy and bulky due to its thermal control devices to obtain the representative temperature such the heaters, temperature sensors, heat pipes, and radiators. In order to provide the exact representative temperature, the heaters and temperature sensors should be installed on the blackbody as closely as possible, and should be small and thin enough not to influence the temperature distribution of the blackbody. The micro-heaters and micro-temperature sensors are the most suitable approach to provide the uniform temperature distribution and the exact representative temperature.

The micro-grooved carbon layer was deposited on a silicon wafer as the blackbody surface that has a high emissivity. The micro-heaters and micro-temperature sensors were fabricated on the backside of the silicon wafer to install them to the blackbody as closely as possible. The MEMS-based spaceborne blackbody system was developed and validated through the function test on the uniformity of temperature distribution and estimation of representative temperature on the blackbody. Applicability of the fabricated spaceborne blackbody system to space missions was validated through the function test before and after space environment tests in this study.

DESIGN AND FABRICATION

On-board blackbody system

The spaceborne on-board blackbody system is shown in Figure 1. The blackbody system is combined with the deploy/stow tilting mechanism. The blackbody system is stowed during the launch and non-calibration mode, while it is deployed by a shape memory alloy spring actuator to be oriented toward the image senor when the calibration is needed [7].

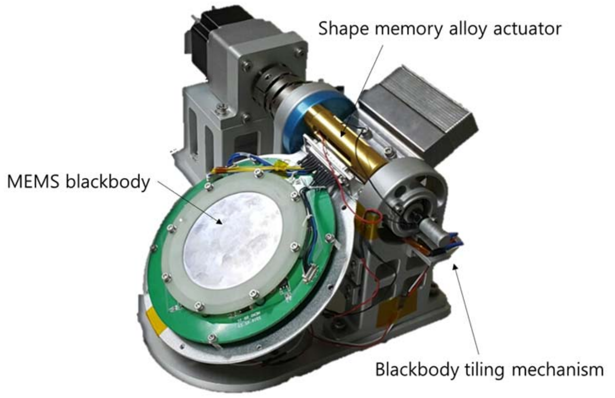

Figure 1: MEMS-based on-board blackbody system combined with the deploy/stow tilting mechanism actuated by a shape memory alloy spring actuator (micro-heaters and micro-temperature sensors were fabricated on the backside of MEMS blackbody).

On the backside of MEMS-based blackbody, the nine micro-heaters and four micro-temperature sensors were fabricated as shown in Figure 2. The heaters and sensors were positioned in the radial direction from the center of wafer and had a shape of serpentine as shown in the inner picture of Figure 2. The size of heater was smaller than that of sensor because their resistance was different. The heater makes a hot spot on a silicon wafer and immediately the heat is spread to make the temperature distribution uniform through the entire area of the silicon wafer. The micro temperature sensor was a resistance temperature detector based on a platinum material [8].

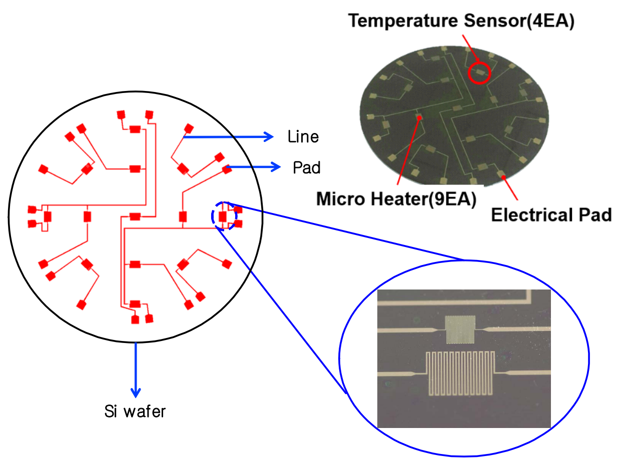

Figure 2: MEMS-based blackbody on the backside of which nine micro-heaters and four micro-temperature sensors were fabricated.

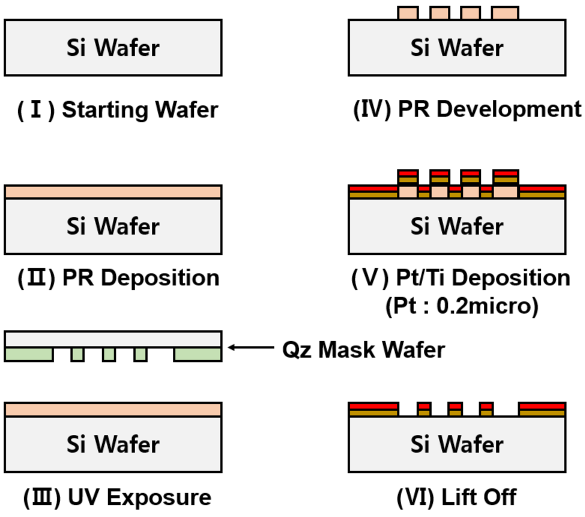

Figure 3: Fabrication processes of the MEMS-based blackbody.

Fabrication of MEMS-based blackbody

The fabrication processes of the MEMS blackbody on the silicon wafer is shown in Figure 3. The process consists of photoresist deposition, ultraviolet exposure through a quartz mask, photoresist development, Pt/Ti deposition by sputtering and lift-off process. The thickness and resistance of Pt/Ti layer were 220 nm and 1,297 Ω, respectively. The specification of the MEMS blackbody is presented in Table 1.

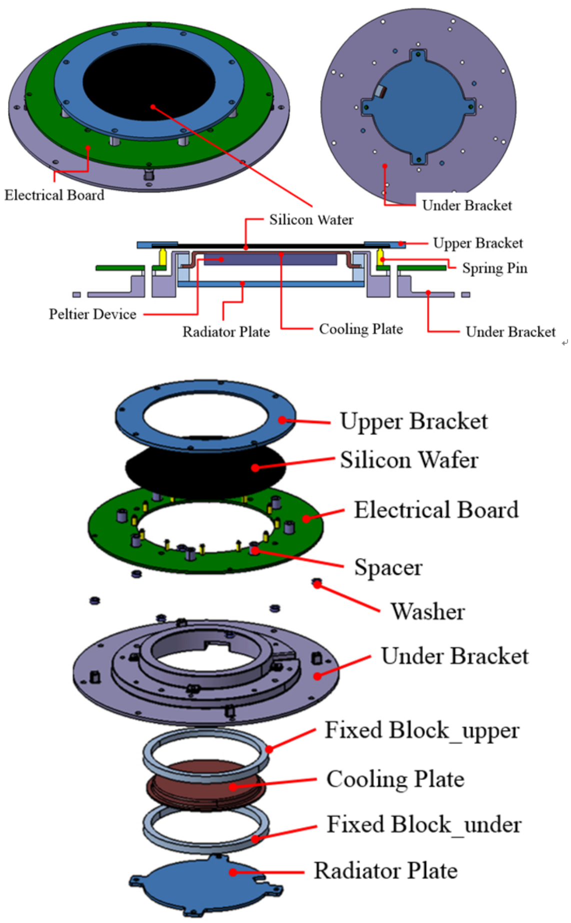

Figure 4: Configuration of the MEMS blackbody system.

Table 1: Specification of the MEMS blackbody.

Description	Unit	Specification
Total mass	g	309
Number of micro heater	EA	9
Type of the heater	-	Serpentine
Thickness of the heater	nm	220
Initial resistance of the heater	Ω	1297

The configuration of the MEMS blackbody system is shown in Figure 4. The fabricated blackbody wafer is placed on spring fins that is connected to the electrical board. The spring fins play a role for the perfect electrical connection between the electrical board and pads of the micro heater and sensors. In addition, it is able to prevent the black body wafer from being broken due to the vibration under the harsh launch environment. The cooling plate was installed underneath the blackbody wafer with a small gap to cool down the blackbody through the radiation cooling, and the Peltier device was attached on the cooling plate for the active cooling.

The assembled spaceborne blackbody system is shown in Figure 5. The control board has a function to activate the micro-heaters which are selectively powered to realize the temperature distribution uniform on the entire surface of blackbody. In addition, the temperature information is transmitted to the main computer through the D-sub connector. The front surface of the blackbody should be coated with a high emissivity material of >0.995. The semi-specular blacking coating is available but its average emissivity is 0.95 which is lower than the required emissivity. The V-groove pattern with 300 μm in width and 18.4° in inclined angle was cut on the black coating. Based on the Monte Carlo analysis, the increase of the emissivity to 0.998 in average was confirmed within the mid-infrared wavelength range as shown in Figure 6.

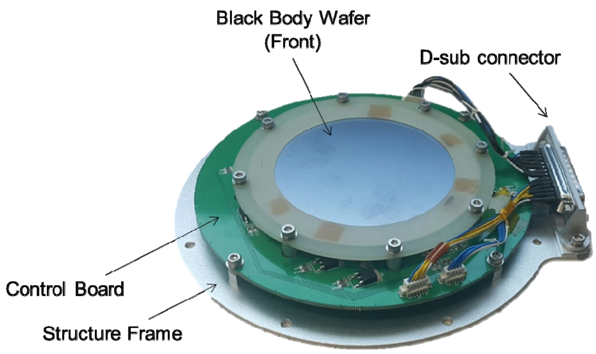

Figure 5: Assembled spaceborne blackbody system.

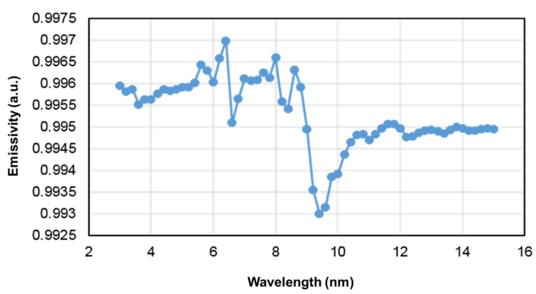

Figure 6: Configuration of the MEMS blackbody system.

FUNCTION TESTS AND PERFORMANCE ESTIMATION

Mass budget of on-board blackbody system

The total mass budget of the MEMS-based on-board blackbody system is listed in Table 2. All of components were included with each material used to manufacture in the list. The total mass of the blackbody system was 0.518 kg which was less than the target mass of 1 kg.

Table 2: Mass budget of MEMS-based blackbody system.

Component	Material	Mass (kg)
Upper Bracket	G10	0.015
Under Bracket	Aluminum	0.2
Spacer	Aluminum	0.005
Upper Fixed Block	G10	0.01
Lower Fixed Block	G10	0.01
Plate for Peltier	Aluminum	0.035
Plate for Radiator	Aluminum	0.03
Washer	G10	0.001
Fasteners	Stainless Steel	0.03
Silicon Wafer	Silicon	0.0095
Peltier Device	Ceramic	0.03
Electrical Board	FR4	0.07
Spring Pin	-	0.003
Harness	-	0.03
Total		**0.518**
Margin (w.r.t Req. of 1 kg)		**0.482**

Temperature profile of blackbody system

Temperature profile of the blackbody system for calibration on the hot and cold cases is shown in Figure 7. The micro-heaters turned on to heat up the blackbody until it reached the target temperature for calibration. Next, the heaters turned off and the temperature was gradually fallen down, from which the calibration was started and finished at the zero temperature. The calibration range was different between the hot and cold cases because the radiation heat transfer rate from the blackbody to the surrounding was different. The calibration range in the cold case was shorter than that in the hot case.

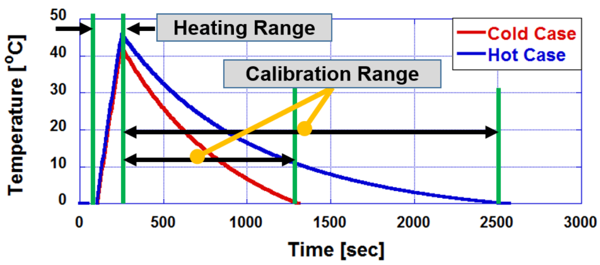

Figure 7: Temperature profile of the blackbody system for calibration on the hot and cold cases.

The temperature contours on the blackbody during the heating and cooling in Figure are shown in Figure 8. The temperature distribution on the blackbody was symmetric in the radial direction so that the radical deviation of temperature could be compensated to estimate the exact representative temperature of the blackbody surface. The estimation accuracy of the representative temperature for calibration in the hot and cold cases is shown in Figure 9. In both hot and cold cases, the estimation accuracies of the representative temperature were less than 0.0001, which means that the exact and precise temperatures can be provided for calibration of image sensors according to the target temperature.

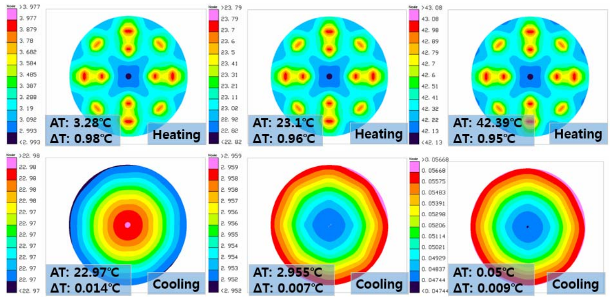

Figure 8: Temperature contours on the MEMS-based blackbody for calibration according to the temperature during the heating and cooling, respectively.

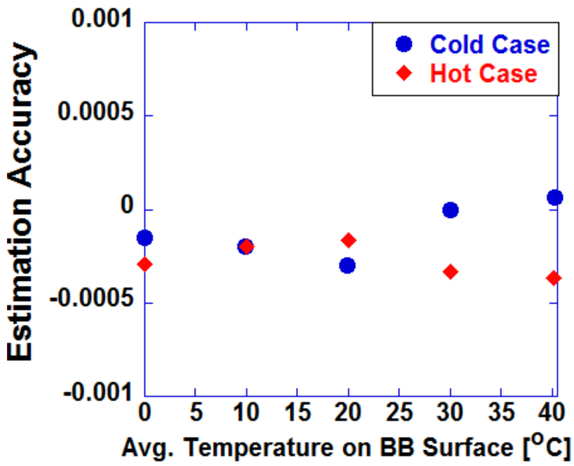

Figure 9: Estimation accuracy of the representative temperature for calibration in the hot and cold cases.

Fail-safe function of the MEMS blackbody system

The temperature uniformity can be worse when even one of micro-heaters is failed which can happens under the harsh launch environment. The temperature gradient when a single micro-heater is failed is shown in Figure 10. The region on the blackbody at which the micro-heater is failed has the non-uniform temperature in comparison of other regions where micro-heaters is working.

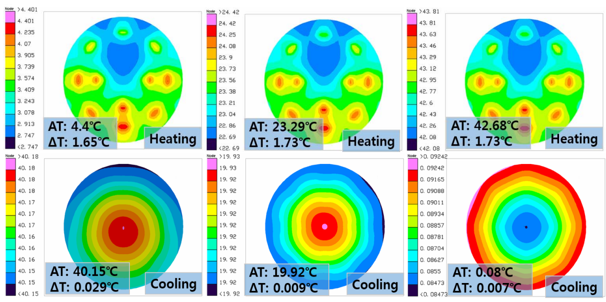

Figure 10: Temperature contours on the MEMS-based blackbody when a single micro-heater was failed.

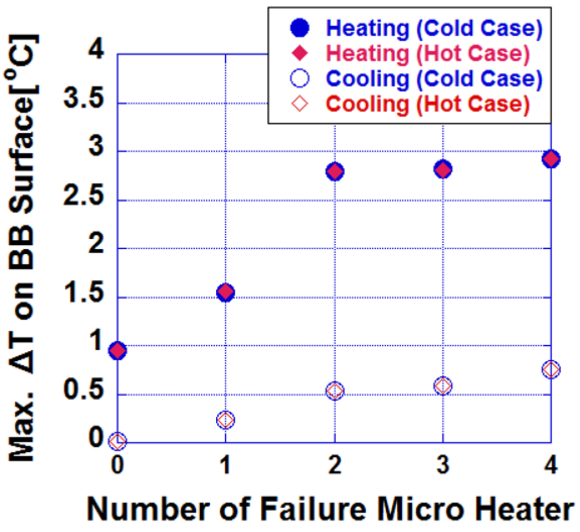

Figure 11: Maximum temperature difference on the blackbody surface under heating and cooling in the cold and hot cases.

However, the temperature difference was 0.029 K at 40.15°C under cooling at which the calibration would be performed, and subsequently the difference decreased as the blackbody temperature was getting down due to the cooling. Finally, the temperature difference was 0.007 K at 0.08°C. The maximum temperature difference on the blackbody surface under heating and cooling in the cold and hot cases is shown in Figure 11. When even one of micro-heaters is failed, the other micro-heaters should be controlled by turning on and off to make the temperature distribution on the blackbody surface be uniform within 0.1 K.

CONLCUSION

MEMS-based multifunctional spaceborne blackbody system was developed for on-board calibration of image sensors in space applications. The blackbody surface was fabricated on the silicon wafer because of its high thermal conductivity. The micro-heaters and micro-temperature sensors were fabricated on the backside of the blackbody to improve the accuracy in estimating the temperature of the blackbody surface. Consequently, the on-board blackbody system featuring a lightweight, low power consumption, high accuracy was realized. The temperature uniformity within 0.01°C was achieved so that the exact representative temperature of the blackbody surface could be provided for the wide-range temperature calibration of image sensors.

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