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Thermal Radiation Control by Surface Gratings as an Advanced Cooling System for Electronic Devices*

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Abstract

Recently, the spectral properties of thermal radiation have been controlled by surface gratings having a size in the optical wavelength range, and this technique has been applied to improve the efficiency of energy systems, e.g., thermophotovoltaic generators and sky radiators. In this paper, the technique was applied to an advanced cooling system for electronic devices. In general, electronic devices are packaged in resin to protect them from damage; however, resin prevents heat from escaping from the package because of resin's strong absorption of thermal radiation in the infrared range and low thermal conductivity. By controlling the spectral property of thermal radiation from electronic devices, the thermal radiation absorbed by resin can be decreased. As a result, a cooling system for electronic devices is possible. At first, we performed a numerical simulation to design the optimal surface gratings to cool electronic devices packaged in epoxy resin. The surface gratings were fabricated using a MEMS process. The performance of the fabricated emitter was evaluated experimentally. In conclusion, we confirmed that this new cooling technique will be effective for electronic devices.

Key words: Electronic Devices, Thermal Radiation, Spectrally Selective Emitter, Periodic Two-Dimensional Surface Gratings, MEMS Process, Microcavity Effect, Epoxy Resin

1. Introduction

Thermal energy is transferred by the three forms, conduction, convection, and radiation. Thermal radiation is the phenomenon in which a body radiates electromagnetic waves according to various parameters such as its temperature and emissivity. In contrast to the other two forms of heat transfer, for thermal radiation, it is necessary to consider not only the heat flux but also the intensity profile of the wavelengths. The intensity profile is ruled by Planck's law; the spectrum is broad in the large-wavelength range because of spontaneous emission and incoherent radiation. Thermal radiation is an important factor in energy systems such as a sky radiator(1) and thermophotovoltaic generation system(2)(3). In these systems, if the radiation spectrum is intense only within a specific wavelength range, the radiation energy can be utilized more efficiently.

Recent progress in quantum optics and nanotechnology has made control of the thermal radiation spectrum possible. A device that enables this control is called a spectrally selective emitter. Thus far, various types of spectrally selective emitters have been proposed

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and studied, such as material-based selective emitters[(3)-(8)], multi-layered selective emitters[(9)-(13)], and microstructured selective emitters [(14)(15)]. It is well known that spectral emissivity depends on surface morphology. For example, a rough surface shows higher emissivity than a polished surface. More complicated spectral control can be realized by using well-defined microstructures such as periodic surface gratings. In the optics community, surface gratings and photonic crystals are widely researched and developed to realize optically functional devices such as filters, lenses, optical switches, and lasers. Recently, some groups have attempted to apply these materials to the spectral control of thermal radiation[(3)(16)]. The microstructured selective emitters have potential advantages such as adjustability of spectral design and adaptability to various materials. Therefore, this selective emitter is very attractive for various thermal systems in which thermal radiation plays a main role in heat transfer. In our study, we applied a microstructured selective emitter to develop an advanced cooling system for electronic devices.

It is well known that the heat density of electronic devices as represented by the central processing unit (CPU) has increased rapidly with increment in power consumption and miniaturization of device size. For example, the heat density of CPUs used in supercomputers reaches approximately that of a nuclear reactor core. But the temperature of electronic devices needs to be maintained at approximately 100°C or below. Therefore, cooling electronic devices becomes a very difficult but important issue; hence, a new cooling technology is desired.

Given these considerations, we propose a new concept for a cooling system for electronic devices by focusing on thermal radiation. Many types of electronic devices are packaged in resin to protect them from vibration, dust, and moisture. However, the resin prevents thermal radiation from electronic devices because it absorbs heat strongly at various bands in the infrared (IR) region, as shown in Fig. 1. This absorption in the IR region increases the temperature of not only the resin but also the devices. The absorption bands of the resin, however, are narrow and show strong wavelength dependence; thus, we can find a wavelength range where absorption is very small. If thermal radiation from the device occurs only at the appropriate wavelength range by using the spectrally selective emitter, as shown in Fig. 1, then the radiation can be directly exhausted out of the package. As a result, the electronic device is expected to stay cooler.

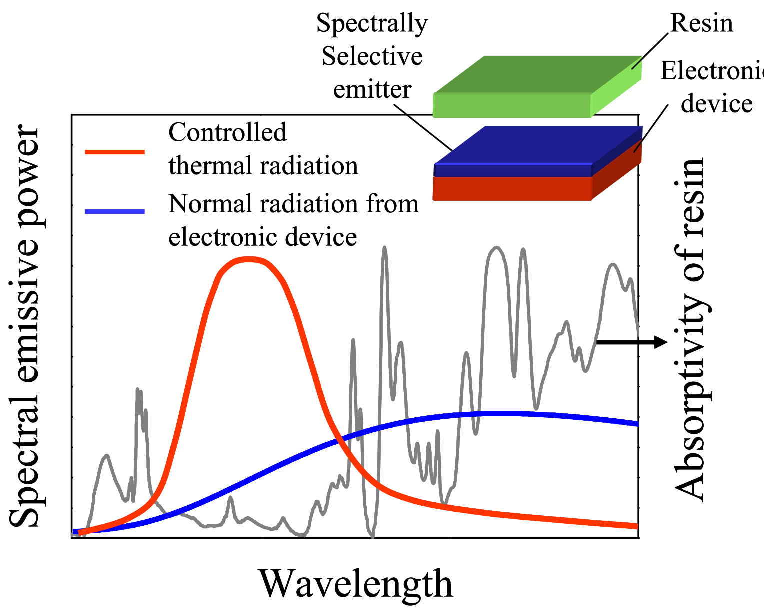

Fig. 1 Schematic illustration of the concept of this study. The inset shows the placement of components.

The objective of this study is to clarify the performance of a new cooling technique that uses a spectrally selective emitter. For this purpose, we fabricated the emitter and performed cooling performance tests. The optimal parameters for the surface gratings of the emitter were designed on the basis of numerical simulations.

2. Experimental

2.1 Design of spectrally selective emitters

Microstructured selective emitters control thermal radiation by the interaction between electromagnetic waves and microstructures with size in the optical wavelength range. One of the main interactions is the microcavity effect(17)(18). In detail of the effect, in the microcavities of the appropriate size, standing electromagnetic waves exist. Thus, absorptivity, regarded as emissivity by Kirchhoff's law, in the electromagnetic waves of the wavelength range that is able to exist in microcavities increased, while in contrast, in the electromagnetic waves of the wavelength range that is not able to exist in microcavities reflected. Therefore, the microcavity effect is strongly related to microstructures' geometry. Thus, the wavelength range where spectral emissivity shows a high value can be controlled by designing the emitter's surface profiles such as microcavity size, shape, and pitch.

The emitter's optical property was predicted by numerical simulation using the rigorous coupled-wave analysis (RCWA) method(19). In the model used in the calculation, rectangular microcavities were lined periodically on the surface, as shown in Fig. 2 (a). The aspect ratio a/d and aperture ratio a/Λ are fixed at 1.0 and 0.6, respectively, in the model. In consideration of the fabrication process (discussed later), the model consists of a silicon substrate and a platinum coating. The result of calculation is shown in Fig. 2 (b). The peak of spectral emissivity is shown in red. The peak shifts to a larger wavelength with increase in aperture size a.

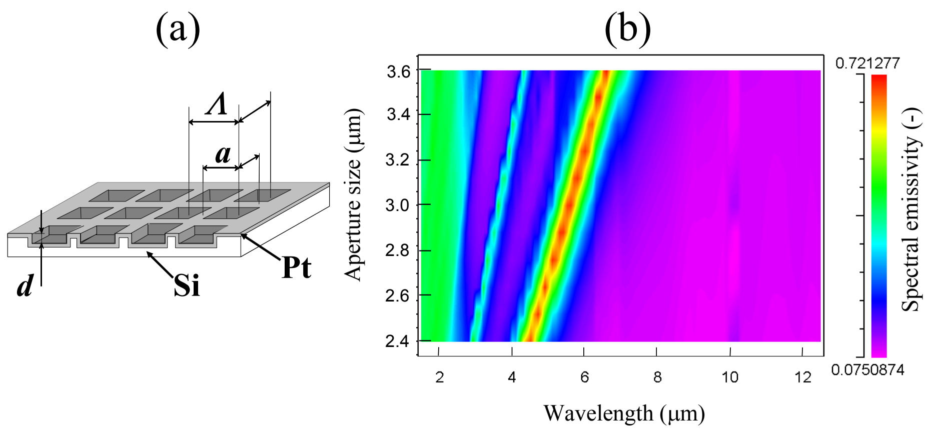

Fig. 2 (a) Model of numerical simulation.
(b) Aperture-size dependence of spectral emissivity distribution.

The estimation of emitter performance is complicated using the calculated optical property for various parameters of the surface gratings because the performance depends on not only energy absorbed by the resin but also the total emissive power from the electronic device. In other words, if the emissivity peak position varies, both absorbed energy dependent on the absorptivity spectrum of the resin and total emissive power based on Planck's law change. Therefore, to evaluate the performance, we defined the cooling performance value η as shown in Eq. (1).

$$\eta = \frac{E^{\alpha}_{Blackbody} - E^{\alpha}_{Selective}}{E^{\varepsilon}_{Blackbody} - E^{\varepsilon}_{Selective}} \tag{1}$$

$E^{\varepsilon}_{Blackbody}$ shows the emissive power of a blackbody integrated in wavelength range from 0 μm to 25 μm.

$E^{\varepsilon}_{Selective}$ shows the emissive power of a spectrally selective emitter,

$E^{\alpha}_{Blackbody}$ shows the energy absorbed by the resin when a blackbody is used,

and

$E^{\alpha}_{Selective}$ shows the energy absorbed by the resin when a spectrally selective emitter is used.

Then, $E^{\varepsilon}_{Selective}$, $E^{\alpha}_{Blackbody}$, and $E^{\alpha}_{Selective}$ are given by Eqs. (2), (3), and (4)

$$E^{\varepsilon}_{Selective} = \int_0^{25} \varepsilon_\lambda \cdot E^{\varepsilon}_{Blackbody,\lambda} d\lambda \tag{2}$$

$$E^{\alpha}_{Blackbody} = \int_0^{25} \alpha_\lambda \cdot \varepsilon_\lambda \cdot E^{\varepsilon}_{Blackbody,\lambda} d\lambda \tag{3}$$

$$E^{\alpha}_{Blackbody} = \int_0^{25} \alpha_\lambda \cdot \varepsilon_\lambda \cdot E^{\varepsilon}_{Selective,\lambda} d\lambda \tag{4}$$

where

ε_λ : spectral emissivity of a spectrally selective emitter,

α_λ : spectral absorptivity of an epoxy resin,

$E^{\varepsilon}_{Blackbody,\lambda}$: spectral emissive power of a blackbody,

and

$E^{\varepsilon}_{Selective,\lambda}$: spectral emissive power of a spectrally selective emitter.

In Eq. (1), the denominator indicates the difference in total emissive power between a blackbody and the spectrally selective emitter, and the numerator indicates the difference in the energy absorbed by the resin between the case when using a blackbody and that when using the spectrally selective emitter. The emitter is expected to show a high performance; that is, η should be large. Each term was calculated using the RCWA results and the absorptivity spectrum of epoxy resin, which is mainly used for the package material.

2.2 Fabrication of spectrally selective emitter

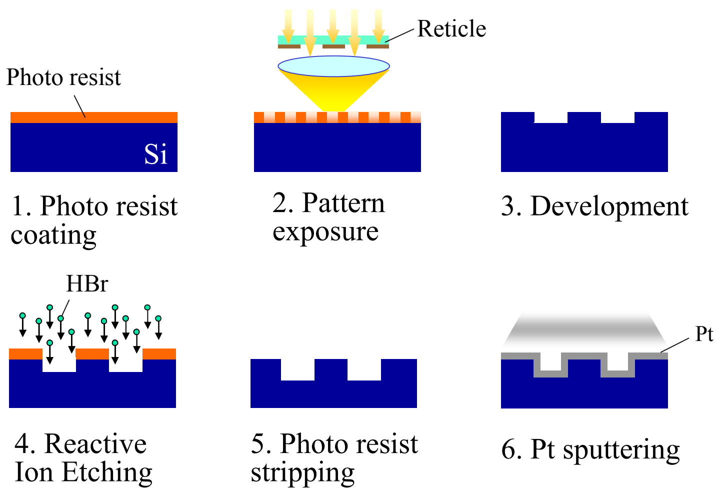

Fig. 3 Process flow diagram of the fabrication process of the surface gratings.

The surface gratings with a size in the optical wavelength range were fabricated by a MEMS process on a silicon substrate and were coated by platinum surface of 100 nm thickness. The process flow diagram is shown in Fig. 3. The fabricated emitters' surface morphology was observed by a scanning electron microscope (SEM) and their emissive property was measured by Fourier transform infrared spectroscopy (FT-IR).

2.3 Cooling performance test

Cooling performance was evaluated using a model of an electronic device packaged in resin. A metal heater was used to model the electronic device. The heater was placed in a box made of 2-mm-thick epoxy resin. To observe the radiation effect clearly, the epoxy resin box was placed in vacuum, and some interspaces were made by alumina pipe and firebrick to prevent the heater directly touching with the resin box. The configuration of the apparatus is shown in Fig. 4. The test was performed under constant temperature and input power to the heater. The emitter performance was evaluated by measuring the heater temperature, resin surface temperature, and radiation heat flux from the resin to the outside. The heater temperature was measured by thermocouples and the resin surface temperature was measured by a thermograph (NEC Avio, Thermo Tracer TH6200R). The heat flux was measured by a radiant flux sensor (CAPTEC, RF-50).

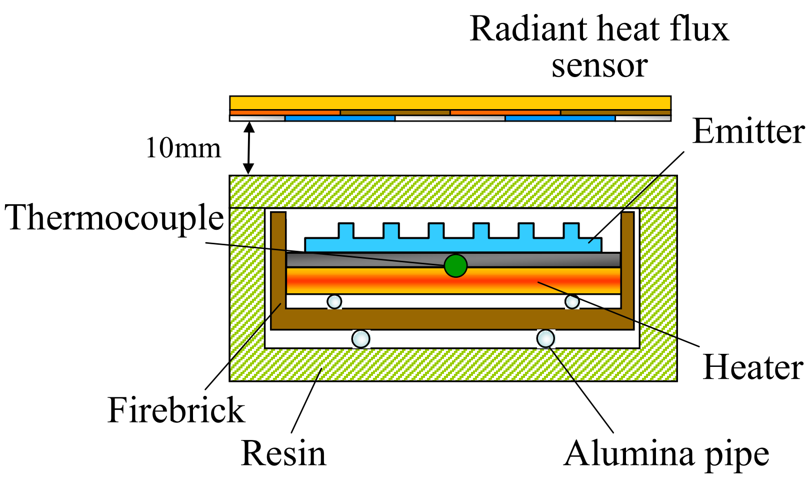

Fig. 4 Schematic cross section of the apparatus for the cooling performance test in vacuum.

In the test, four types of emitters were used to compare their cooling performance. The following were the emitters used: a platinum flat surface emitter, which modeled the general surface of electronic devices; a highly emissive emitter, which showed high emissivity at all wavelengths similar to a blackbody; the optimized spectrally selective emitter, which we expect to have a high cooling performance; and the other spectrally selective emitter, which we regard as a low cooling performance. The surface of each emitter was different. However, because the substrate material of all emitters was silicon, they had approximately the same bulk thermal conductivity.

3. Results and Discussion

3.1 Optimized design of surface gratings

The simulation was performed at various grating aperture sizes. Cooling performance value η was calculated using Eq. (1) assuming the temperature of the electronic device to be 100°C. The calculated spectral emissive power spectra are shown in Fig. 5, and the result of calculated η is shown in Fig. 6.

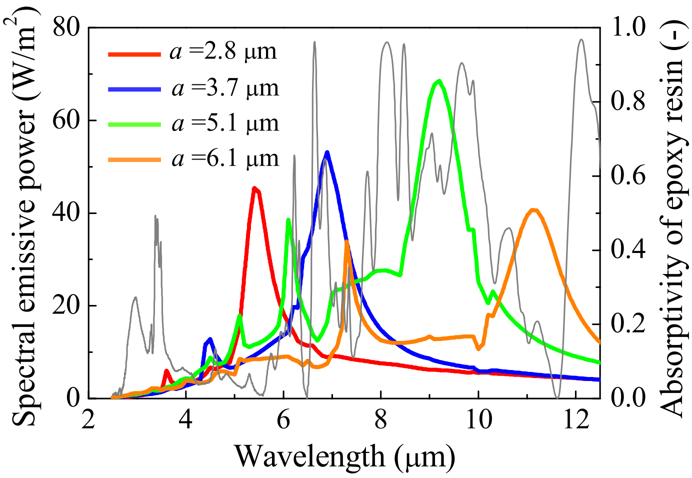

Fig. 5 Spectral emissive power calculated on various emitters with different aperture sizes. The gray line shows the absorption spectrum of the 2-mm-thick epoxy resin.

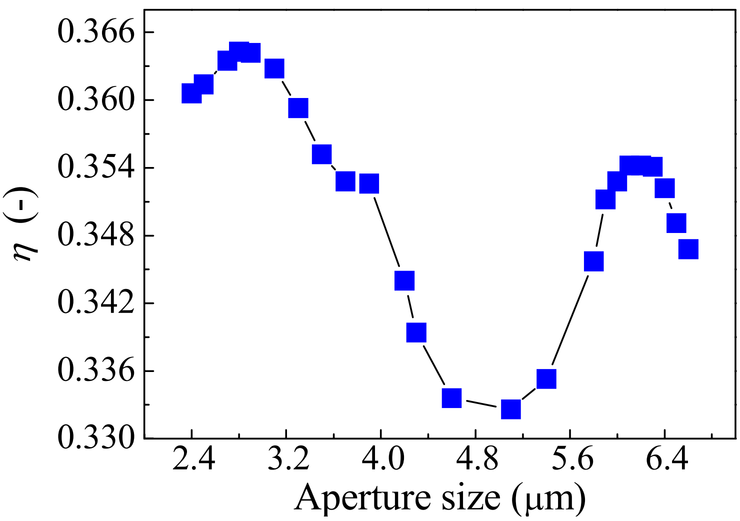

Fig. 6 Calculated cooling performance η of emitters with different aperture sizes.

$E^{\varepsilon}_{Selective}$ apparently had the largest value when the aperture size was around 5 μm, as shown in Fig. 5. However, η had a high value when the position of the emissive peak was in the wavelength range 4−6 μm or 11−12 μm; η had the highest value when the aperture size was 2.8 μm. Thus, the result indicates that the selective emitter that has Λ = 4.8 μm, a = 2.8 μm, and d = 2.8 μm periodic rectangular surface gratings is the optimum emitter for cooling electronic devices.

3.2 Evaluations of the fabricated spectrally selective emitter

For comparison, spectrally selective emitters of aperture sizes 2.8 and 5.1 μm were fabricated by the MEMS process as mentioned above. The SEM images are shown in Fig. 7, and measured emissivity spectra of the fabricated emitters by FT-IR at 573 K are shown in Fig. 8. The fabricated surface gratings show round edges, especially the emitters with small gratings. It can be considered that this phenomenon is caused by the isotropic etching property of HBr gas used in the process. The parameters of these surface gratings were similar to those of the assumed one. Fig. 8 shows that the emissivity peak positions of the fabricated samples were in good agreement with the simulation results. However, the emissivity peak widths of the fabricated samples were larger than those of the simulated samples. It can be considered that the shapes of surface gratings, such as the round edges, were somewhat different from the simulation model; hence, the spectral selectivity was diminished. However, cooling performance value η calculated with the measured spectral emissivity showed a high value of 0.366 for the optimal emitter and a low value of 0.315 for the other emitter.

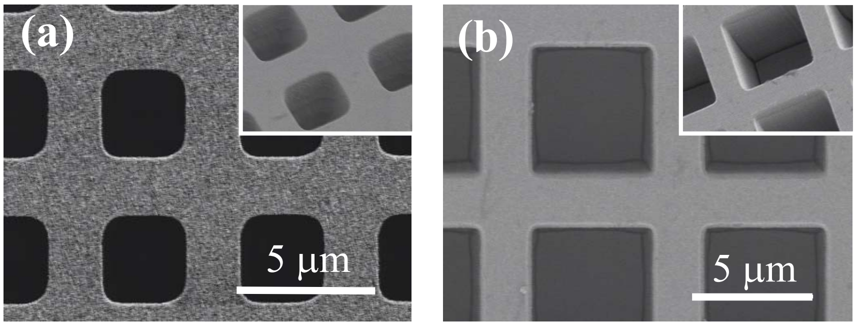

Fig. 7 SEM images with top views and oblique views (insets) of the fabricated spectrally selective emitters with aperture sizes (a) 2.8 μm and (b) 5.1 μm.

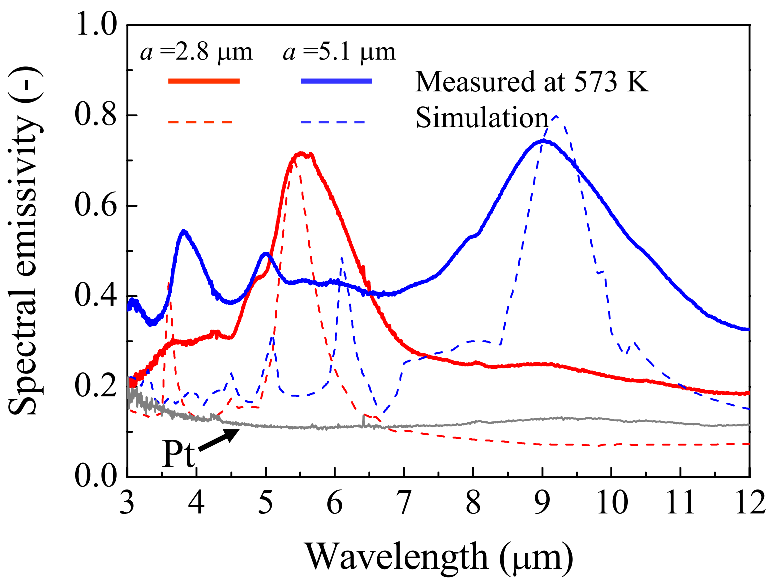

Fig. 8 Measured spectral emissivity spectra of fabricated samples. Red and blue lines show the emitter with aperture sizes 2.8 μm and 5.1 μm, respectively. Solid and dotted lines show the spectral emissivity measured at 573 K and that calculated, respectively. The gray line shows the spectral emissivity of the flat platinum surface.

3.3 Results of cooling performance test

Figure 9 and Table 1 show the results of the cooling performance test. In the test, input power to the heater was maintained at 2.2 W. From Table 1, the heater temperature was decreased 2.7°C by using the optimized spectrally selective emitter compared to platinum flat-surface emitter. Moreover, the heater temperature was decreased 2.1°C by using the highly emissive emitter. The resin temperature was the lowest (75.2°C) when the optimized spectrally selective emitter was used; in contrast, it was the highest (81.5°C) when the highly emissive emitter was used. When the spectrally selective emitter with low-η was used, the heater temperature decreased slightly and the resin's temperature was high (80.1°C). Hence, the reason for the decrement in the heater temperature was not the surface gratings' direct effect such as increase in surface area. Figure 10 shows the amount of energy radiated from the heater to the outside of the package.

Table 1 Heater and resin temperatures of various emitters at cooling performance test

	Heater Temperature (°C)	Resin Temperature (°C)
Platinum flat surface Emitter	124.7	78.8
Highly emissive Emitter	122.6	81.5
Optimal Spectrally Selective Emitter	122.0	75.2
Spectrally Selective Emitter with Low-η	123.7	80.1

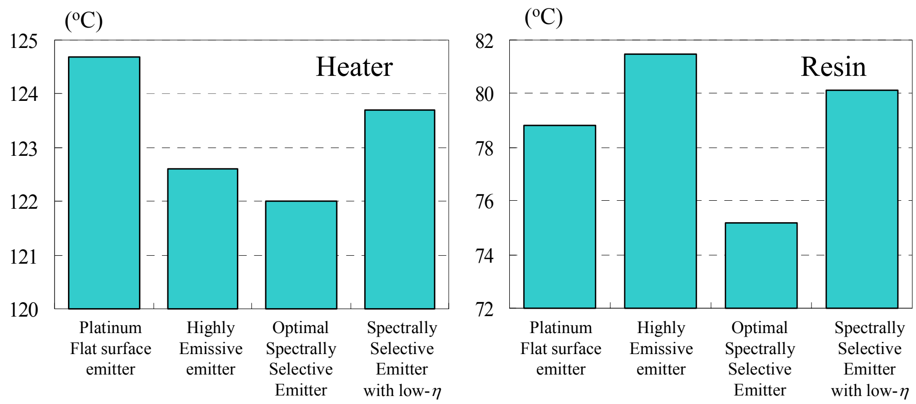

Fig. 9 Result of cooling performance test with four types of emitters.

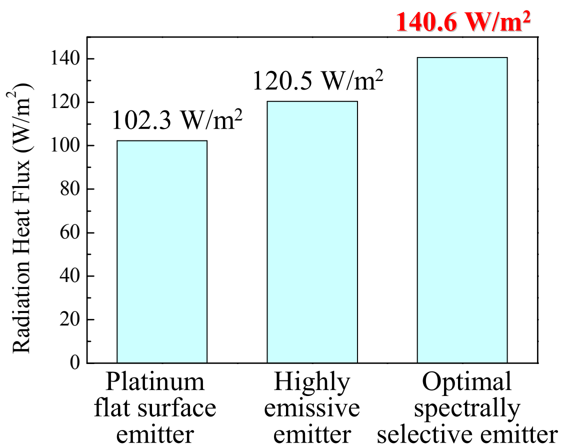

Fig. 10 Result of radiant flux from inside the package measured by a radiant flux sensor.

These results of the cooling performance test indicate that emissive power from the highly emissive emitter would be larger than that from the optimized spectrally selective emitter. However, most radiation from the highly emissive emitter is absorbed by the resin. On the other hand, radiation from the spectrally selective emitter is absorbed less by the resin. The radiant flux from inside the resin was increased by 37% when the optimized spectrally selective emitter was used, compared to the platinum flat surface emitter. The heat flux was also 17% larger than that of the highly emissive emitter. Because of this effect, the radiation energy from inside the package was enhanced by the optimized spectrally selective emitter. Consequently, cooling performance was improved.

4. Conclusion

We presented our new concept of cooling of electronic devices packaged in resin by controlling the thermal radiation spectrum. To confirm our concept, we performed numerical simulation to optimize parameters of surface gratings on the spectrally selective emitter. As a result, we realized that the selective emitter that has Λ = 4.8 μm, a = 2.8 μm, and d = 2.8 μm periodic rectangular surface gratings is the optimal emitter for cooling electronic devices. We fabricated the emitter by a MEMS process. Then, we performed the cooling performance test using four types of emitters. As a result, the temperature of the heater that modeled an electronic device can be decreased by 2.7°C when the optimized spectrally selective emitter is used. The radiant flux from inside the resin can be increased by 37%. From this study, we confirm the cooling performance of our new cooling technique that uses the spectrally selective emitter.

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