Development of spectrally selective infrared emitter for thermophotovoltaic power generation

波長選択機能を有する熱光起電力発電用赤外線源の開発

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1. Introduction

Thermophotovoltaic (TPV) power generation has recently attracted considerable attention as a means to use waste heat [1-4]. In order to improve the efficiency of TPV power generation, it is necessary to develop thermal emitters that selectively emit infrared (IR) photons having energies that match those of the bandgaps of photovoltaic (PV) devices; these devices then convert the IR photons to electricity.

Makino and Wakabayashi [5] have successfully developed simple selective emitters based on a combination of NiO thin films and a Ni substrate; the emittance of the developed emitters in the IR region reaches up to 0.7. Although this value is much larger than the emittance of uncoated Ni, there is scope for obtaining an increase of approximately 0.3. In this study, we have developed efficient emitters having an emittance of nearly 1 at the designed wavelength by using a β-$FeSi_2$ thin film/stainless steel substrate system.

2. Antireflection (AR) coatings for metals

According to Kirchhoff's law on thermal radiation, the spectral emittance of a surface is equal to its spectral absorbance at thermal equilibrium. For a thin film system fabricated on an opaque substrate, emittance ε is described as

$$\varepsilon = 1 - R, \quad (1)$$

where R is the reflectance. An ideal emitter emits only those photons whose energies equal that of the bandgap of the PV device, which is usually in the IR region. Thus, a highly efficient selective emitter has a reflectance spectrum with the minimum at the wavelength corresponding to the bandgap of the PV device, and it exhibits higher reflectance at other wavelengths. Such reflectance spectrum can be achieved by depositing interference AR coatings on highly reflective metal substrates. However, the application of AR coatings to metals has not been investigated intensively. In this section, we discuss the AR conditions for a simple system consisting of dielectric thin film/metal substrate.

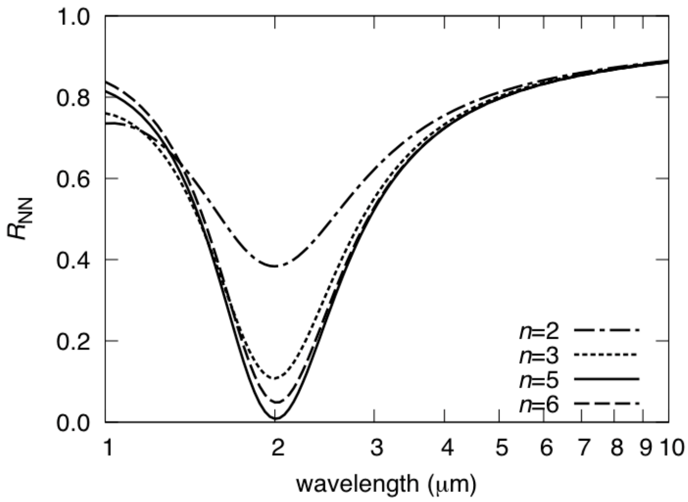

Fig. 1 Calculated R_{NN} spectra of thin films fabricated on SUS304 substrates for n = 2–6.

Fig. 1 indicates the reflectance spectra at normal incidence R_{NN} for dielectric thin films deposited on a metal substrate. In the spectral calculations, the refractive index n of the thin film was varied between 2 and 6, and the optical constants of the substrate were assumed to be identical to those of the SUS304 stainless steel substrate [6]. The thickness of the dielectric films was tuned such that the reflectance attains a minimum at a wavelength of λ = 2 μm. Clearly, the reflectance for n = 5 at λ = 2 μm is the lowest of the four calculated spectra. In addition, the reflectance at shorter or longer wavelength region is kept at high values. Although the refractive indices of most of the conventional optical materials are lower than 2.5, a few semiconductors have higher refractive indices in the IR region. The refractive index of β-$FeSi_2$, which is approximately 5 in the IR region, is particularly high [7]. High refractive index materials such as β-$FeSi_2$ are considered to be appropriate for the AR coating of metals. However, thus far, there have been no reports on AR β-$FeSi_2$ coatings. Thus, we attempt to develop interference AR coatings made of β-$FeSi_2$ in order to realize spectrally selective infrared emitters with high efficiency.

3. Experiment

Thin films of $FeSi_2$ were deposited by DC magnetron sputtering onto a polished SUS304 substrate. The base pressure in the deposition chamber was about 5×10^{-4} Pa. The films were deposited in an Ar pressure of 6×10^{-1} Pa at a discharge voltage of 500 V and a discharge current of 20–40 mA. The substrate temperature during deposition was kept constant between room temperature (RT) and 700 K. The crystal structure of the films was analyzed by X-ray

Table 1 List of samples.

ID	Thickness (nm)	Substrate temperature
A	60	RT
B	99	RT
C	155	RT
D	229	RT
E	48	700 K
F	101	700 K
G	146	700 K
H	225	700 K

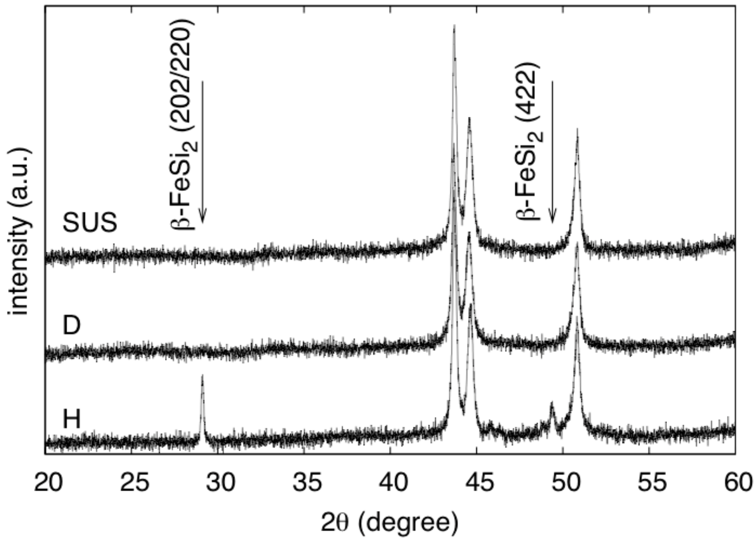

Fig. 2 XRD patterns of samples H (fabricated at 700K), D (fabricated at RT), and SUS304 substrate.

diffraction. The fabrication conditions of samples are listed in Table 1. The reflectance spectra of the specular reflection at an angle of incidence of 15°, $R_{15°(-15°)}$, were measured at RT and 700 K in air to evaluate the performance of the emitters.

4. Results and discussion

Fig. 2 shows the XRD patterns of samples D, H, and the SUS304 substrate. In the XRD pattern of sample H, we observe two peaks at 2θ = 29.12° and 49.40°, which correspond to the (202)/(220) and (422) diffractions of β-$FeSi_2$ [8], respectively, whereas no peaks other than those observed in the XRD pattern of the SUS304 substrate are observed in case of sample D.

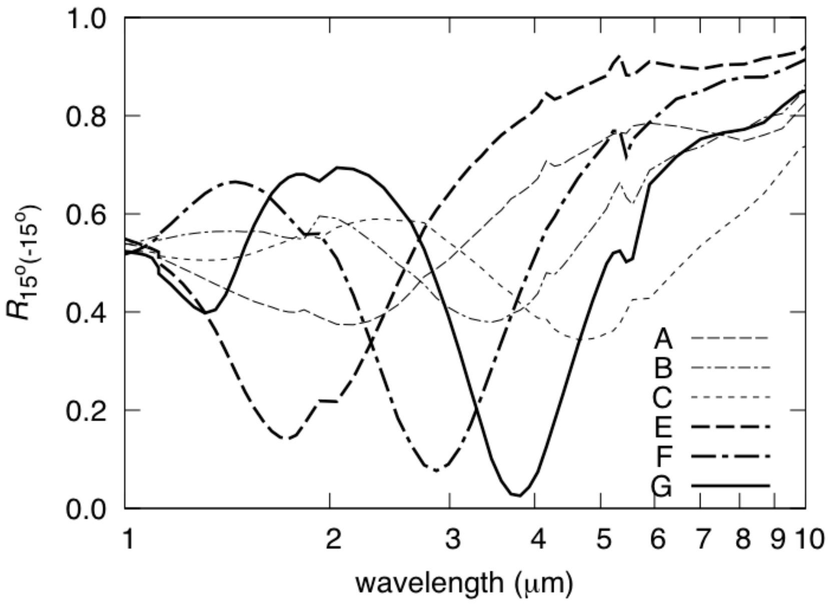

Fig. 3 Reflectance $R_{15°(-15°)}$ spectra of samples E–G (fabricated at 700 K) and samples A–C (fabricated at RT) measured at RT in air.

We confirmed that the diffraction peaks due to β-$FeSi_2$ are observed for the samples whose substrate temperatures exceeded 700 K.

The reflectance spectra of samples A–G are shown in Fig. 3. Although all the samples show minimum reflectance in the IR region, the reflectance of the samples fabricated at RT (samples A–C) are always higher than 0.3. This is due to the fact that the crystallographic structures of samples A–C are not β-$FeSi_2$ but amorphous, and therefore, the refractive index of the films is likely to be much different from that of β-$FeSi_2$. On the other hand, the reflectance spectra of samples fabricated at 700 K (samples E–G) contain thin films of β-$FeSi_2$ and show a deep minimum (0.142 for E, 0.077 for F, and 0.026 for G). Thus, the AR coating for metals is successfully realized by using β-$FeSi_2$ thin films.

In order to utilize for IR emitters for TPV generation, the AR characteristics in the IR region are required to be maintained at high temperatures in air. Fig. 4 indicates the reflectance spectra of sample G measured at RT and 700 K. No significant difference is found between these spectra. In addition, we confirmed that the reflectance spectra at 700 K are quite stable for more than 15 min. Therefore, metals with AR coatings of β-$FeSi_2$ can be effectively used in IR emitters employed for TPV power generation.

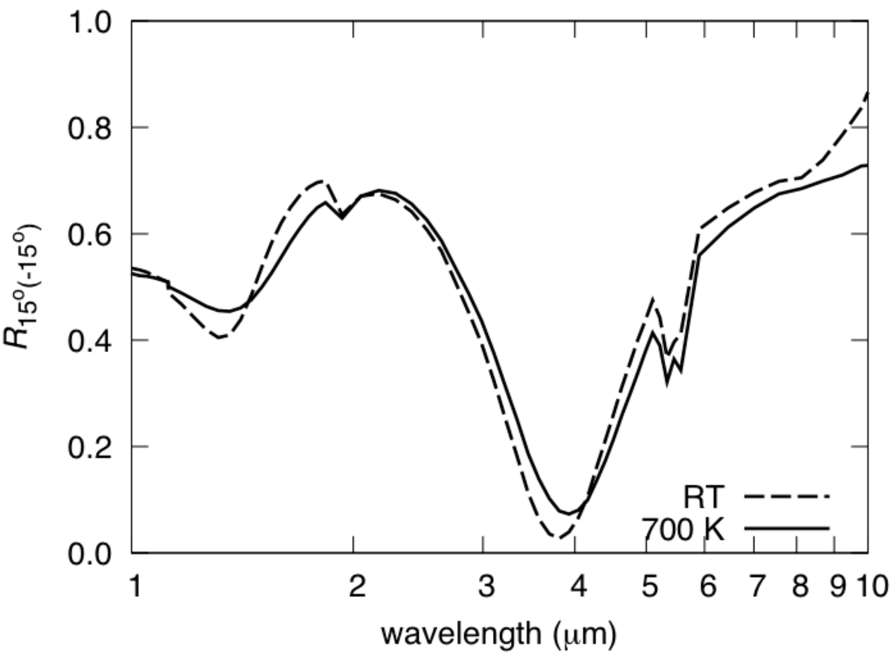

Fig. 4 Reflectance $R_{15°(-15°)}$ spectra of sample G (fabricated at 700 K) measured at RT and 700 K in air.

5. Conclusion

We investigated spectrally selective IR emitters that can be utilized for TPV power generation by using a high refractive index material such as β-$FeSi_2$. The interference AR coating for SUS304 was successfully realized by using a β-$FeSi_2$ thin film. In addition, samples with β-$FeSi_2$ AR coatings were stable at 700 K. Therefore, we concluded that the β-$FeSi_2$/SUS304 system is effective for IR emitters that follow Kirchhoff's law on thermal radiation.

Acknowledgments

We acknowledge Yasuyuki Kaneko and Professor Yoshihito Maeda of Kyoto University for useful discussions. This work was supported by JFE 21st Century Foundation.

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