

Thermophotovoltaic generation with selective radiators based on tungsten surface gratings

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Two-dimensional surface-relief gratings with a period of 1.0–0.2 μm composed of rectangular microcavities were fabricated on single crystalline W substrates to develop spectrally selective radiators for thermophotovoltaic generation. The radiators displayed strong emission in the near-infrared region where narrow-band-gap photovoltaic cells could convert photons into electricity. The enhancement of thermal emission was attributed to the microcavity effect. Power generation tests were carried out and the W gratings showed more than two times higher generation efficiency, compared to a SiC radiator. The results showed that the microstructured W radiators behave as good selective radiator, with both high efficiency and high power density. © 2004 American Institute of Physics. [DOI: 10.1063/1.1807031]

Thermophotovoltaic (TPV) generation has attracted attention as a new endeavor in the photovoltaic (PV) and thermal engineering fields.¹ In TPV systems, thermal radiation from a radiator is converted into electricity using PV cells. A key issue in developing high-performance TPV generators is the spectral matching between the radiator's thermal radiation spectrum and the PV cell's spectral response, which usually lies between the visible and the near-infrared (NIR) regions. For this purpose, spectrally selective radiators, whose emissivity is high only in the PV cell's sensitive region and low outside it, have been studied by many researchers.²

Recently, it has been demonstrated by several groups that the thermal radiation's spectral feature can be controlled by surface gratings or photonic crystals.^{3–8} They have utilized several interactions between thermal radiation and modulated surfaces such as surface plasmon polaritons,^{3,4} surface phonon polaritons,⁵ the microcavity effect,^{4,6,7} and photonic band gaps.⁸ Our group has reported that two-dimensional (2D) tungsten (W) gratings composed of microcavities can behave as selective radiators for TPV applications due to the cut-off effect of microcavities.⁷ Microstructured selective radiators have potential advantages such as adjustability of spectral design and adaptability to various materials, and therefore further progress is expected. In this study, TPV generation tests are carried out with microstructured W selective radiators with different structural parameters.

Maruyama *et al.* proposed that peak wavelengths on thermal emission spectra from microcavities with an aperture are given by⁶

$$\lambda_{lmn} = \frac{2}{\sqrt{(l/L_x)^2 + (m/L_y)^2 + (n/2L_z)^2}},$$

where l , m , and n are integers ($l, m=0,1,2,\dots$ and $n=0,1,3,5,\dots$) and $L_x \times L_y \times L_z$ denotes the size of microcavities ($L_x \times L_y$ is the aperture size). At most one of the integers can be zero. The maximum value of λ_{lmn} is called

the cut-off wavelength, λ_c . Only photons with wavelengths of $\lambda < \lambda_c$ can exist inside microcavities, and hence an increase of emissivity is expected in that region. The optimum spectral feature of radiators is dependent on the kind of reference TPV cell. In this study we have tried to develop a selective radiator for GaSb, which is one of the typical TPV cells operating in the wavelength region from 0.8 to 1.8 μm .

Selective radiators with 2D surface gratings were fabricated on single crystalline W substrates by means of the electron beam (EB) lithography and fast atom beam etching techniques as described in the previous report.⁷ The structural parameters of the samples are listed in Table I. Since λ_c of our samples is ranged from 1.6 to 1.9 μm , emissivity increase is expected in that region. The grating area is limited to about $\phi=1$ mm because of the drawing speed of the EB lithography system used in this study.

Figure 1 shows a scanning electron micrograph and the reflectivity spectra of the samples measured with a diffuse reflection geometry which can collect the reflected ray to within about $\pm 20^\circ$ from the center angle (PIKE, easidiff). It is confirmed in the micrograph that rectangular microcavities are formed in symmetry to the x and y directions on W surfaces. As plotted in Fig. 1, reflectivity of all the gratings decreases drastically for $\lambda < 2.0$ μm , keeping high reflectivity at longer λ . Multiple local minima are also observed on the spectra, and they shift with deepening or widening microcavities. This reveals that these reflectivity minima originate from the microcavity effect.

Figure 2 shows the schematic diagram of the emission measurement system used in this study. Thermal emission spectra from heated samples are measured by a Fourier transform infrared spectrometer (Perkin Elmer, GX2000). During

TABLE I. Structural parameters of the W gratings.

Sample	Period (μm)	Aperture (μm)	Depth (μm)
A	1.0	0.8	0.7
B	1.2	0.9	0.63
C	1.2	0.95	0.78

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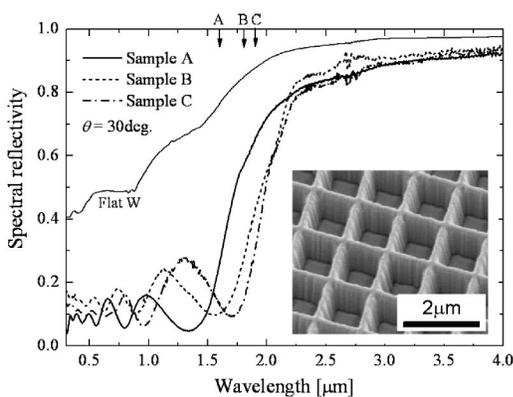


FIG. 1. Spectral reflectivity of the W gratings and flat W at the incident angle of 30° measured with a diffuse reflection geometry at room temperature. The incident beam is randomly polarized. The downward arrows denote λ_c for the three gratings. The inset shows a scanning electron micrograph of sample C.

heating samples, Ar gas with 5% H_2 is passed through the heater casing to prevent oxidation. Sample temperature T is measured with a radiation thermometer. In the case of W gratings whose emissivity is unknown, T is determined by measuring T of the flat part around the grating. For TPV generation tests, we use an InGaAs photodiode (Hamamatsu photonics K.K., G8370-03) with the sensitive region of $0.9\text{--}1.7\ \mu\text{m}$ and the size of $\phi=0.3\ \text{mm}$ as a TPV cell. After measuring emission spectra, the InGaAs diode is inserted in the optical path and I-V characteristics are measured. Thermal durability of such microstructures is quite important for practical applications under a high-temperature environment. We did not observe any degradation of the microstructured radiators throughout the experiments up to 1400 K. For much higher temperatures, Schlemmer *et al.*⁹ reported that surface coating with thermally stable oxides such as HfO_2 is effective in preventing the thermal deformation of surface microstructures.¹⁰ This is also applicable to our radiators, although they have no coatings in this study.

Figure 3 shows the spectral directional emissivity in the normal direction $\epsilon'_{\lambda n}$ for the samples measured at high T together with data for flat W taken from the literature.¹⁰ $\epsilon'_{\lambda n}$ of all the samples increases drastically for $\lambda < 2.0\ \mu\text{m}$; clear emission peaks are observed on the spectra at $1.22\ \mu\text{m}$ for sample A, at $1.48\ \mu\text{m}$ for sample B, and at $1.56\ \mu\text{m}$ for sample C. These spectral properties correspond to those of the spectral reflectivity shown in Fig. 1, but the peak positions are shifted to shorter wavelengths. A maximum emissivity of over 0.8 is obtained for all the samples. These results showed that the W gratings behave as spectrally

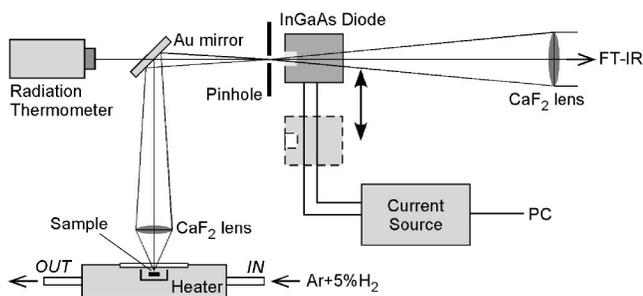


FIG. 2. Schematic diagram showing the apparatus for the emission measurement and TPV generation demonstration.

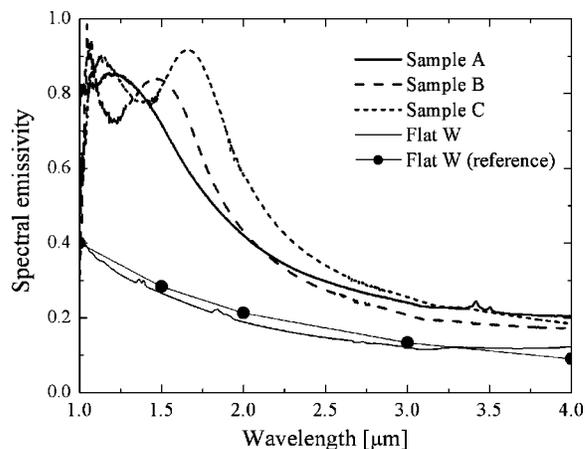


FIG. 3. Spectral emissivity of the W gratings and a flat W at the normal direction. Solid line with circles represents an emissivity spectrum reported in the literature Ref. 10.

selective radiators for TPV applications and can control their spectral feature by adjusting the cavity shape. On the other hand, the measured $\epsilon'_{\lambda n}$ in the infrared region is somewhat higher than that expected from the reflectivity shown in Fig. 1. Based on Drude theory, increasing T causes the reduction of the electron relaxation time τ in metals and results in the increase of $\epsilon'_{\lambda n}$.¹¹ It is also expected that reducing τ increases the skin depth of metals, and hence the confinement modes in microcavities will spread across a large wavelength range. Taking these matters into consideration, it is expected that the spectral property of the W gratings as a selective radiator becomes worse at high T .

The performance of selective radiators is usually evaluated with selective emission efficiency η_{SE} , which is defined by the ratio of the emissive power radiated in the convertible region of the reference PV cell to the total emissive power. Figure 4 shows η_{SE} of the W gratings and flat W as functions of T . In this figure, the region is set to $0.9\text{--}1.7\ \mu\text{m}$, where the InGaAs photodiode is sensitive. In the calculation of η_{SE} , spectral emissive power outside the measurable region ($1.0\text{--}6.0\ \mu\text{m}$) is extrapolated. The W gratings display a significant increase of η_{SE} compared with a graybody radiator such as SiC, due to the emissivity increase in the NIR region. The degree of η_{SE} increase is larger than that of other conventional selective radiators like rare earth materials.

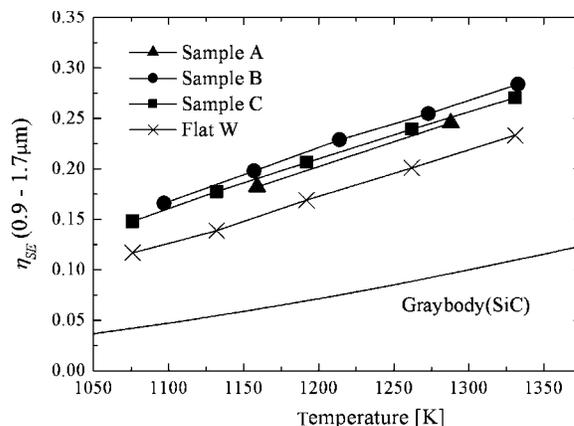


FIG. 4. Selective emission efficiency of the W gratings, flat W, and SiC for $\lambda=0.9\text{--}1.7\ \mu\text{m}$ as functions of radiator temperature.

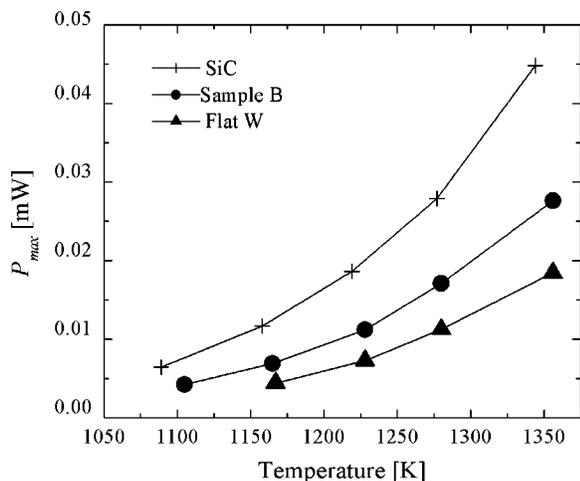


FIG. 5. P_{max} of the InGaAs photodiode radiated by several radiators as functions of radiator temperatures.

Figure 5 shows the maximum output power P_{max} obtained by TPV generation tests as functions of T . A sufficiently large fill factor of over 0.7 was observed for all data, while only a small P_{max} ($\mu\text{W} \sim \text{mW}$) was obtained, mainly due to the small area of the photodiode and radiators, and the large distance between them. For all radiators, P_{max} increases rapidly with increasing T since total emissive power is generally proportional to T^4 . Sample B gives larger P_{max} than a flat W radiator because of its higher emissivity in the NIR region. However, SiC, which is a typical broad-band radiator with an emissivity of 0.9, gives the maximum P_{max} among the three radiators at a constant temperature.

The most important parameter in TPV systems is the input energy-to-electricity efficiency. In this study, however, it was difficult to determine the amount of input power which was used to heat samples because their size is much smaller than that of the heater. At high T over 1000 K, thermal radiation is dominant when compared with thermal conduction and convection. Thereby it can be supposed that the input thermal energy to heat a radiator is approximately proportional to the emissive energy from its surface. In Fig. 6, P_{max} is replotted as functions of the total emissive power incident on the diode, EP_{total} . Sample B reaches higher T and gives much larger P_{max} than SiC at constant EP_{total} because of its spectral selectivity. The ratio of P_{max} to EP_{total} , namely, the slope in Fig. 6 gives a relative evaluation of the conversion efficiency from the input energy to electricity. The figure shows that sample B will achieve two times or much higher efficiency than SiC.

Sample B emits about 20 kW/m^2 in $\lambda=0.9\text{--}1.7 \mu\text{m}$ at 1400 K. Assuming the radiator-to-cell view factor of 0.7 and the PV cell's efficiency of 0.5 in that region, we can develop a 100 W TPV generator with microstructured W radiators with an area of 140 cm^2 . The area is reduced to 110 cm^2 for the same system with a SiC radiator, but it needs about three times larger input energy to keep T . In other words, W gratings can provide higher T and larger output power under the same input energy.

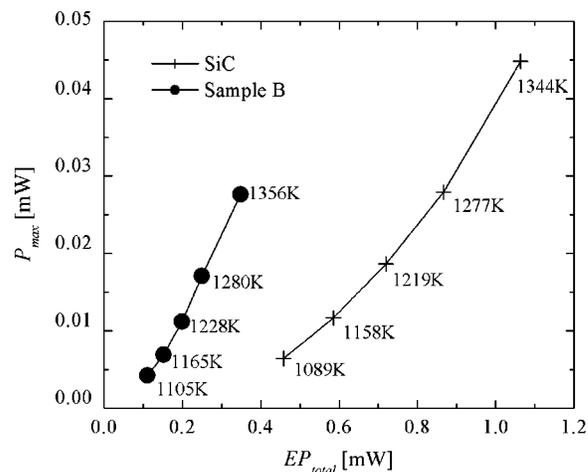


FIG. 6. P_{max} of the InGaAs photodiode radiated by several radiators as functions of the total incident emissive power, EP_{total} . The numbers beside the symbols denote radiator temperatures.

In summary, the spectral properties of W were successfully controlled based on the microcavity effect introduced by 2D W surface gratings composed of microcavities. It was confirmed experimentally that the W selective radiators have advantages for high-power and high-efficiency TPV systems. The studies on fabrication processes for large area devices will be the next target. From this point of view, 2D surface gratings are more suitable than three-dimensional photonic crystals.⁹ Spectral control by surface gratings can be applied to various energy conversion systems at a wide range of temperatures, such as incandescent lamps, solar absorbers, thermo-chemical engineering, and radiation cooling. Further studies will lead to developing practical devices for these applications.

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