THERMAL RADIATION CHARACTERISTICS OF SILICON INVERSE OPAL IN MID INFRARED RANGE

XU Jing, LI Yujie，Liu rongsheng and Xie Kai
Department of Material Engineering and Applied Chemistry, National University of Defense Technology, Changsha 410073, P. R. China.

Introduction

In recent years, photonic crystals has stimulated wide interest because it can control the thermal radiation, which could provide a wide range of applications[1] like solar cell, thermophotovolatic power generation, thermal control of satellite, sensor, lasers etc. In 2003, Shawn Yu[2]reported their experimental study on the emission spectra of tungsten woodpile structure. The results indicate that the photonic crystal emission is suppressed obviously in the photonic band gap regime(λ>3μm) and the emission is enhanced at a narrow band near 1.5μm. The optical-to-electric conversion efficiency of TPV based on GaSb cells could be improved to an estimation of ~34%. In 2004, Hitoshi Sai[3] from TOHOKU University investigated the control effect of tungsten two dimensional photonic crystals on the emission. As an important kind of three dimensional photonic crystal structures, the band structure and optical properties of reflectivity and transmittance from inverse opal has been studied widely. In contrast, few studies have dealt with their emission performance. In this letter, a silicon inverse opal is obtained with a complete photonic band gap at mid refrared region. And the infrared radiation characteristic of resulted sample is examined.

Experimental

All solvents and chemicals are of reagent quality. Monodispersed silica spheres with diameters of 2100nm were purchased commercially. Flat silicon wafer are used as substrates. Prior to use, the silicon wafers are soaked in a boiling mixture of sulfuric acid and hydrogen peroxide (3:1,v/v) for 15 minutes, rinsed well with ultra pure water, and dried in a stream of high nitrogen.

2100nm monodisperse SiO_2 microsphere was dispersed in a kind of binary solvents with large density by continuous sonication. Flat silicon substrate was placed vertically into the above solution, which was subsequently placed in a temperature-controlled bench of 60℃. After the solvent was evaporated, the SiO_2 opal template was obtained on the surface of silicon substrate.

Silicon was infiltrated by the low pressure chemical vapor deposition method using SiH_4 as a precursor[4]. The deposition temperature was 823K. The flux of SiH_4 was 1ml/min and the flux of N_2 as transportation gas was 4ml/min. The deposition time was 1 hour. Then the infiltrated template was annealed at 600℃ for 10 hours to transform amorphous silicon into polycrystalline silicon. Finally, the silica template was removed by submerging it in a mass fraction of 2% HF in water solution for 12 h and silicon inverse opal was obtained.

The structural analysis of the sample was performed by scanning electron microscope (SEM, model JSM 5600LV). The emission spectra of the samples were taken using a 102F Fourier transform IR spectrometer of D&P.

Results and discussion

Fig.1 shows scanning electron micrographs (SEM) of the top surface of a silicon inverse opal fabricated from a face-centered cubic (FCC) array of 2100-nm silica spheres. Interconnected porous structure is visible through the pores and shows a long range order. The diameter of an air sphere in silicon inverse opal is approximately 2100nm. The micro scale structure has inherited the long range FCC order of the original opal template.

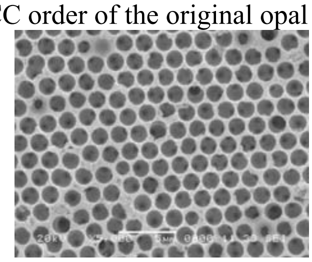

Fig 1 SEM image of a silicon inverse opal.

Emission measurements were performed by heating silicon inverse opals to ca.250℃ in an ambient atmosphere. The emission spectra of silicon inverse opal on flat silicon substrate are collected by the FTIR microscope. Fig 2 shows the thermal radiation spectra of silicon inverse opals and bulk silicon wafer taken at the same condition. Compared to the thermal emission of bulk silicon, the spectra of inverse opal shows suppressed emission at λ=3.6-4.2μm (the shadow region in the figure2) and enhanced emission at λ=4.6-5μm and λ=8.0-10.0μm. In both spectra, the absorption peak at λ=4.2-4.3μm is due to the absorption of carbon dioxide in atmosphere. The emission measurements indicate that the structure of inverse opal play an important role on the thermal radiation of silicon.

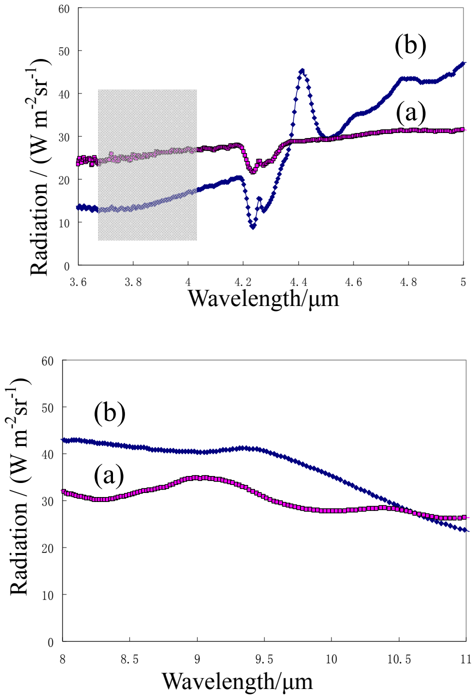

Fig 2 Radiation spectra of silicon inverse opal(a) and bulk silicon wafer (b)

To investigate the influence of photonic band structure on emission properties, the band gap structure of silicon inverse opal is simulated. Figure 3 is the simulated photonic band structure of silicon inverse opal for all directions with an infiltration ratio 100%. The simulations equations are compiled by Band solve software based on the Plane Wave Expansion Method. We use n=3.45 as the refractive index of polycrystalline silicon and 0.3536 as the normalization radius of the air sphere. The simulated result shows that a complete three-dimensional bad gap exits between band8 and band9 (the shadow region in the figure3).

The lattice constant of inverse opal shown in figure 1 is 2970nm. According to the simulated photonic band structure, the center wavelength of the complete band gap is λ_{band8}-λ_{band9}=3750nm (a/λ=0.7918) and the width is Δλ=200nm. So, the suppressed emission at λ=3.6-4.2μm is probably due to the photonic band gap effect of Si inverse opal. The suppression is indicative of the absence of photonic DOS in the band gap regime that forbids the emission of infrared radiation in all 4π angles. It is noted that the emission intensity at the pass band wavelengths (λ~4.6-5.0μm and λ~8.0-10.0μm) for silicon inverse opal exceeds that of flat silicon emission by about 30%. The observed emission enhancement for silicon inverse opal may be attributed to the photonic transmission resonances. The above results are consistent with the previous experimental results on silicon photonic crystals with diamond crystal symmetry [5].

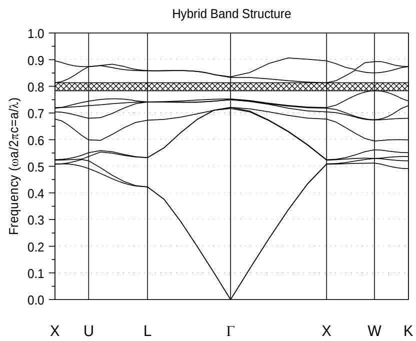

Fig 3 Simulated photonic band structure of silicon inverse opal.

Conclusion

A silicon inverse opal is obtained with a complete photonic band gap at mid refrared region. The SEM image indicates the orderly porous structure of silicon is formed. The silicon inverse opal structure is observed to be highly effective in suppressing silicon thermal radiation in the photonic band gap spectral regime. Emission is also enhanced in the photonic pass bands.

Reference

1. J. G. Fleming, S. Y. Lin, I. El-Kady, R. Biswas & K. M. Ho .*Nature*, **417**(2002)52
2. Shawn Yu L Moreno J and Fleming J G *Appl. Phys. Lett.*, **83**(2003)380
3. Hitoshi Sai,Hiroo yugami,Yasuhiro akiyama,et al. *Nanoscale and Microscale Thermophysical Engineering*, **2**(2003)101-115.
4. Yu-Jie Li, Kai Xie, Jing Xu, Pan-Pan Du. *Applied Physics A Materials Science & Processing*, **99** (2010) 117-123.
5. Shawn Yu L Fleming J G Chow E Bur J., *Phy. Rev. B*, **62**(2000)R2243