Demonstration of multilayer titanium photonic crystals with 100-nm feature sizes

Shich-Chuan Wu [a], Chuan-Ding Lin [a], Yu-Lin Yang*[b], Jing-Shian Chen [a], and Yang-Tung Huang [b]
[a]National Nano Device Laboratory, 26 Prosperity Road I, Science-based Industrial Park, Hsinchu, Taiwan, R.O.C.
[b]Department of Electronic Engineering and Institute of Electronics, National Chiao-Tung University, 1001 Ta-Hsueh Road, Hsinchu, Taiwan, R.O.C.

ABSTRACT

Multilayer titanium photonic crystals are fabricated with the mature integrated circuit (IC) technology, which is similar to the Damascene interconnect process. The photonic crystals that we created have the face-centered-tetragonal lattice symmetry. In each layer, the feature size, height and the spacing of the titanium rods is 100 nm, 200 nm and 300 nm, respectively. To our knowledge, this is at the first time that the three-dimensional titanium photonic crystals are realized successfully with 100-nm line width. The reflectance spectra of three- and four-layer titanium photonic crystals are measured with the Fourier-transform infrared spectroscopy and simulated with the three-dimensional finite different time domain method. Through both the experimental observation and the calculation verification, the characterization of the photonic band gap is demonstrated at near-infrared wavelengths and the optical behavior of titanium photonic crystals is discussed for incident light waves of s- and p-polarization. Moreover, the absorption spectra are derived from the reflectance and transmittance spectra due to the law of conservation of energy. It is found that absorption near the photonic band edge is modified and enhanced in a narrow bandwidth because of the well-known recycling-energy mechanism. The large band gap can suppress black body radiation in the mid-infrared range and recycle energy into the near infrared. According to Kirchoff's law, the absorptance of a body equals its emissivity. Thus, the multilayer titanium photonic crystals would be applied as an efficient near-infrared light source with a narrow bandwidth, and produced on a mass scale with the standard IC technology.

Keywords: Metallic photonic crystals, nano optics.

1. INTRODUCTION

Photonic crystals (PCs) are artificial materials with periodic changes in the dielectric constants, analogous to crystal structures of semiconductors, and the photonic band gaps (PBGs) can be created for certain ranges of photonic energies [1]. Three-dimensional (3D) PCs can provide complete band gaps, in which the propagation of electromagnetic waves is prohibited for all wave vectors. Among a variety of proposed 3D PC structures, the so-called woodpile structure is attractive for its large PBG and simple design rule [2]. This structure has been successfully realized with dielectric materials by some state-of-the-art technologies, such as wafer bonding [3], multiphoton lithography [4] and atomic layer deposition [5]. Metallic PCs have been investigated for the last decade. The special electromagnetic phenomenon, as efficient light sources, has been demonstrated [6] due to their large band gaps and the absorbing properties. Such a large band gap could suppress broadband blackbody radiation at the mid-infrared wavelengths, and recycle its energy into the high frequency range. Therefore, it has been suggested that 3D metallic PCs may be useful for the incandescent lamp application and the thermal photovoltaic power generation [7]. However, fabricating 3D metallic PCs in a large scale is still a challenge.

In this report, we use mature integrated circuit (IC) technology, which is like Damascene interconnect process to accomplish 3D titanium photonic crystals with 100-nm feature sizes. By means of this method, 3D Ti PCs can keep good quality in an area of 5×5 mm. To probe the PBG properties of 3D titanium PCs, we use a Fourier-transform infrared (FTIR) spectrometer to measure polarization dependence of the samples, and confirm the measurement results by the 3D finite-difference time-domain (FDTD) method. Moreover, thermal emission spectra taken from the 3D titanium PCs are shown and compared to the measured reflectance spectra.

*ylyang.ee93g@nctu.edu.tw; phone 886-3-5712121 ext.54212; fax 886-3-5724361

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2. FABRICATION PROCESS

The 3D PC that we created has face-centered-tetragonal (FCT) lattice symmetry [2], which consists of simple parallel titanium rods with a pitch of *a* in each layer. The orientation of rods in one layer is perpendicular to that in successive layer. The rods in one layer are shifted by *a*/2 with respect to that in the second-nearest neighboring layer. In this report, *a* is equal to 300 nm. The width and the height of titanium rods are 100 nm and 200 nm, respectively. The flow chart of fabrication process is shown in Fig. 1. First, a 200-nm thick titanium layer is deposited by a physical vapor deposition (PVD) system (ULVAC Sputter, SBH-3308RDE). After a lithography process by an electron beam writer (Lecia, Weprint 200 type) and a reactive ion etching (RIE) process (ILD-4100), the pattern of parallel rods are transferred from a mask to the titanium layer. Then, a silicon dioxide film is deposited by a process of high density plasma chemical vapor deposition (Duratek system, Multiplex Cluster CVD) to fill titanium trenches. This is followed by a process of chemical-mechanical polishing (Westech, model 372M) to remove the excess silicon dioxide over the titanium trenches. The same processes are repeated layer-by-layer as desired to accomplish the multilayer PCs. The scanning electron microscope (SEM) images of the 3D titanium PC is shown in Fig. 2.

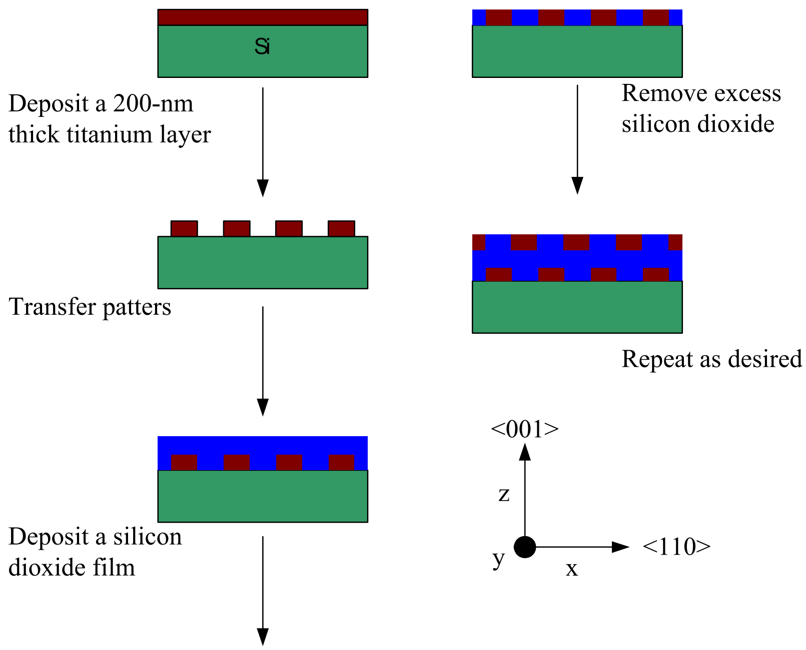
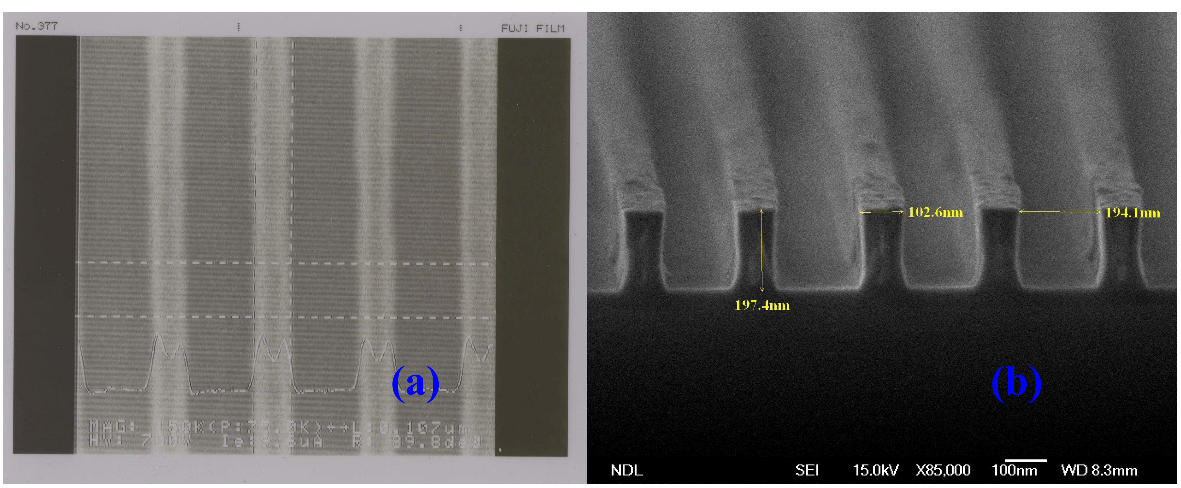


Fig. 1 Process flow of fabricating the 3D titanium PCs.



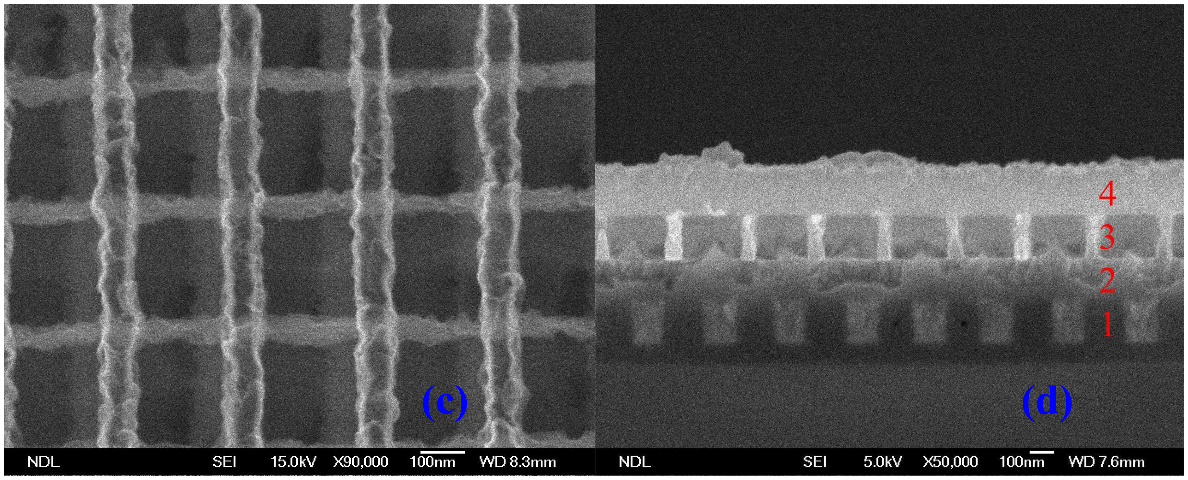


Fig. 2 SEM images of the 3D titanium PCs. (a) Top view and (b) cross-sectional view of the single layer titanium PC. (c) Top view and (d) cross-sectional view of the four-layer titanium PC. The width and height of titanium rods are 100 nm and 200 nm, respectively. The rod-to-rod spacing is 300 nm. Some misalignment appears between the second-nearest neighboring layers, such as the second and the fourth layers. The rod width of the third layer is reduced due to deviation in the RIE process for the titanium film.

3. RESULTS AND DISCUSSION

3.1 Measured Spectra at Normal Incidence

To investigate the PBG behaviors of 3D titanium PCs, we measure the samples by the FTIR spectrometer (BRUKER H2K) at normal and grazing incidence of light. This FTIR spectrometer is equipped with a KBr beamsplitter and a mercury-cadmium-telluride (MCT) detector for mid-infrared wavelength range. When measuring for near-infrared wavelength range, the beamsplitter and the detector would be changed as a CaF_2 beamsplitter and an InGaAs detector. In our experiment, the reflectance spectra as shown in Fig. 3, are normalized to that of a gold mirror.

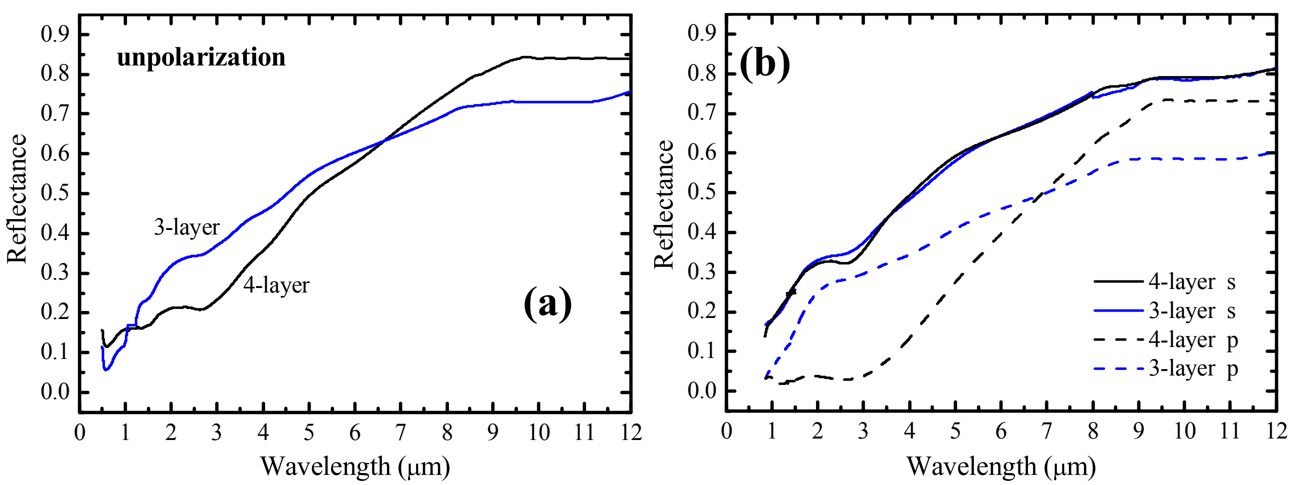


Fig. 3 Measured reflectance spectra of the 3D titanium PCs at normal incidence. The incident light is (a) unpolarized, (b) s and p polarized. In this report, s- and p-polarization is defined as the electric field of incident light parallel and perpendicular to extension direction of titanium rods in the most upper layer, respectively.

The four-layer titanium PC exhibits higher reflectance than the three-layer one for wavelengths ≧ 7 μm, and the reflectance decreases sharply at shorter wavelengths. It can be seen that the four-layer sample shows clearer PBG behavior than the three-layer one, because the four layer structure forms a unit cell of a FCT lattice. As shown in Fig. 3(a), the photonic band edge locates at a wavelength of 5 μm (where reflectance = 0.5) for the 3D titanium PC along the

<001> axis. Comparing with a 3D copper PC [8], a titanium PC exhibits a band edge at longer wavelengths. Since the plasma frequency of titanium is lower than that of copper, intrinsic absorption from titanium metal plays an important role at wavelengths < 7 μm, resulting in the band edge of the titanium PC locating at a wavelength much longer than its feature size. To understand the material dependence on the PBG, we consider the simplest case, reflection and absorption by metal films. The reflectance at the interface of metal and air for the case of normal incidence is given by

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}, \tag{1}$$

where n and k are the real and imaginary parts [9] of dielectric constants of metal, respectively. We assume that the metal film is very thick to ignore the transmission of light through it. The absorptance A is equal to 1-R, and the calculated results are shown in Fig. 4. It is found that the copper is more suitable for constituting a 3D PC with a band edge at near-visible wavelengths because of high reflectance in the infrared range. In order to apply 3D PC in the visible range, scaling the dimensions down is another necessary approach. However, fabricating uniform structures with below 200-nm feature sizes in a large area is still a challenge to block development of functionality for 3D metallic PCs.

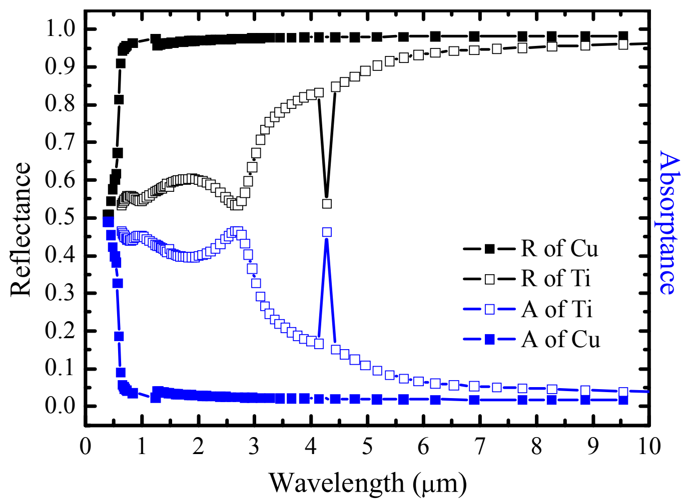


Fig. 4 Calculated reflectance and absorptance spectra of copper and titanium films. The abnormal reflectance and absorptance values at a wavelength of 4.28 μm are calculated results based on the dielectric constant of titanium.

To probe the polarization dependence on the PBG of the 3D titanium PCs, the reflectance spectra of three- and four-layer samples are measured with illumination of s- and p-polarized light, as shown in Fig. 3(b). For s-polarized light, the reflectance spectra from these two samples are almost identical in the measured wavelength range. This is due to the waveguide cutoff effect in the most upper layer of titanium rods [10]. As the s-polarized light is incident to the samples, the reflection and absorption from the surface layer dominates the entire optical behavior. On the other hand, the reflectance spectra of three-layer and four-layer samples are rather different for p-polarized light. As the layer number of titanium rods increases, the PC provides higher reflection at longer wavelengths due to increase of titanium. In the range of wavelengths <7 μm, the absorption of titanium metal becomes significant to cause lower reflectance values for the four-layer titanium PC. Besides, more complete the FCT lattice structure is, more obviously the PBG effect shows. At the band edge, the group velocity of light is slower, resulting in a longer light-matter interaction time and enhanced absorption by titanium metal. Therefore, reflectance of the four-layer structure decreases substantially near the band edge. In general, a 3D PC can have a complete band gap, in which s- and p-polarized light is forbidden to propagate in the PC region. From our measured results, it is clear that the PBG of p-polarization dominates the range of the complete band gap for the 3D metallic PC.

3.2 3D FDTD Computation

Fig. 5 shows the computed results for the four-layer titanium PC, which is of the same dimensions with the fabricated one. We perform the simulation with the 3D FDTD method by commercial software (RSoft). The grid sizes are set as 10 nm in the *xy*-plane and 18 nm in the stacking direction of the 3D PC structure. The dielectric constants of titanium are taken from values in [9]. The boundary condition is set as the perfect matching layers and input source is a continuous plane wave. The computed results agree with the measured results except the higher reflectance values at shorter wavelengths. In particular, the dip at a wavelength near 3.0 μm in the reflectance spectra stems from higher absorption of titanium near this wavelength. This is also observed in the measured reflectance spectra. As shown in Fig. 5(a), the absorptance A is derived from reflectance R and transmittance T (A=1-R-T). In the range of wavelengths < 8 μm, absorption increases significantly. This phenomenon is primarily due to the characteristics of titanium metal and the PBG effect. Fig 5(b) shows the computed results of polarization dependence on the PBG effect. Both reflectance spectra for s- and p-polarization match with the measured ones, and the computed transmittance spectra for two cases are close.

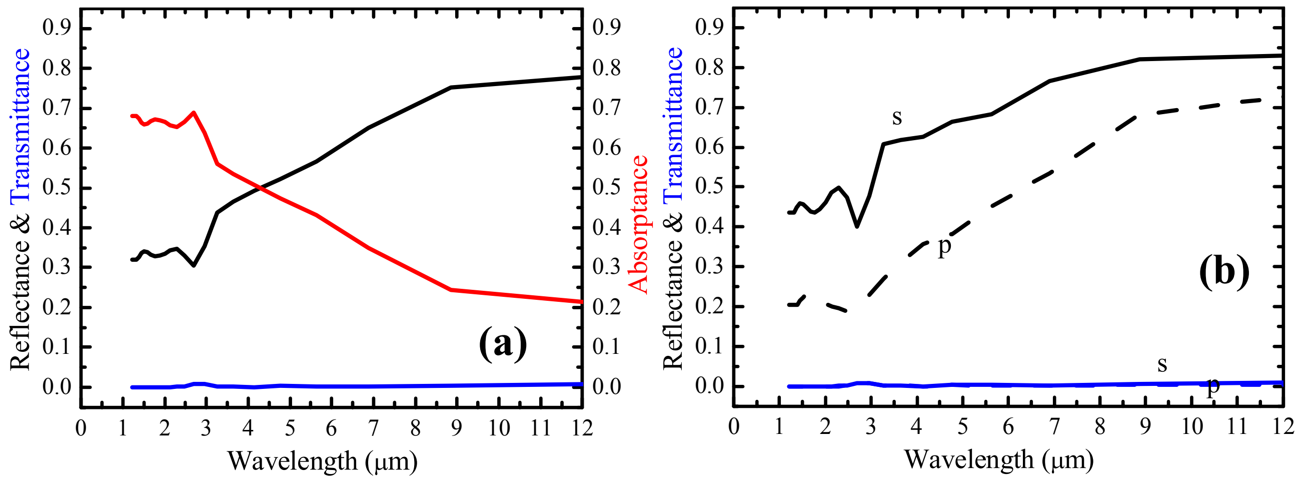


Fig. 5 Computed reflectance, transmittance and absorptance spectra of the four-layer titanium PC for (a) unpolarized, (b) s- and p-polarized light.

3.3 Measured Spectra at Grazing Incidence

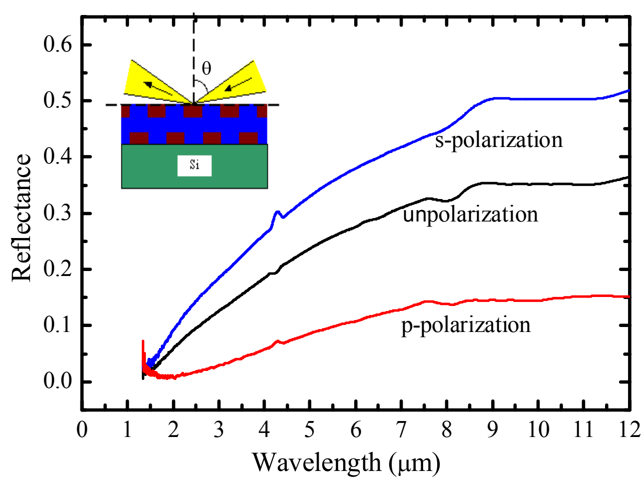


Fig. 6 Measured reflectance spectra of the four-layer titanium PC at grazing-angle incidence. The angles of incidence beam is from 52.2° to 84.2° at a time. The tilt-angle geometry is as shown in the inset.

To investigate the effect of tilted angle for the 3D titanium PC, we use the grazing incidence objective in the FTIR spectrometer. The angle of incident beam is from 52.2° to 84.2° at a time. Fig. 6 shows the measured results of grazing-angle incidence. It can be seen that the reflection decreases for polarized and unpolarized light, especially for p-polarization. The band edge for the unpolarization case is slightly shifted to a longer wavelength in such large tilted angles of incident light. For s-polarization, the reflectance keeps 0.5 at wavelengths > 8 μm and goes down to a very low value at a wavelength of 1.5 μm. On the other hand, the reflectance is lower than 0.2 in the measured wavelength range for p-polarization, and no clear band edge is observed. This may be attributed to layer number dependence on the PBG of the four-layer titanium PC. A unit cell of FCT lattice is only sufficient for supporting a PBG of p-polarization in the stacking direction of a 3D PC. For providing the forbidden bands in other symmetrical directions of a 3D lattice, increasing the layer number of titanium rods is necessary to constitute a more complete FCT lattice.

3.4 Measured Spectra of Thermal Emission

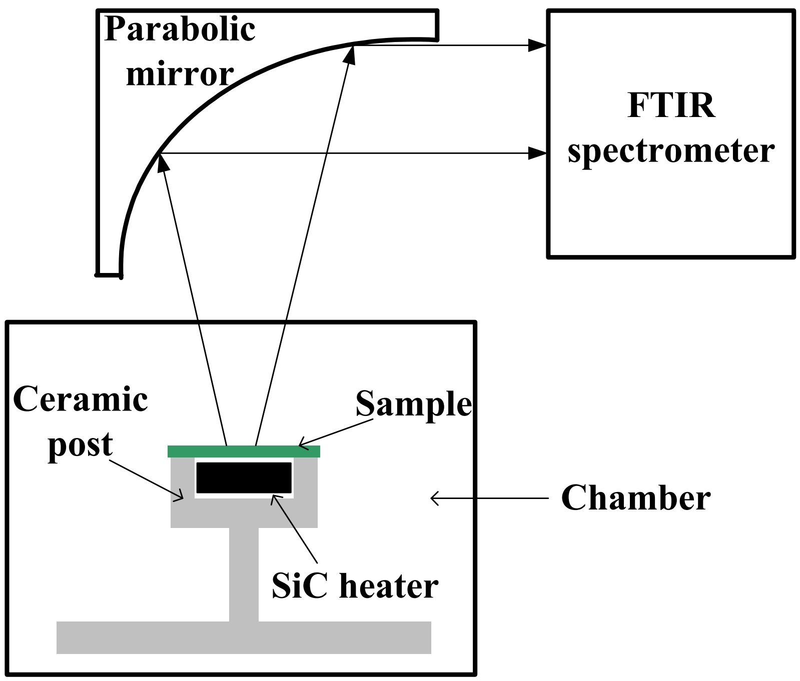


Fig. 7 Schematic diagram of the thermal emission measurement setup.

A 3D metallic PC is recently attractive because it can be designed to modify its absorption property. Its absorptance peak would appear in a narrow wavelength range. According to Kirchoff's law, the absorptance of a body equals its emissivity. Thus, a 3D metallic PC has potential to be applied as an efficient light source with a narrow bandwidth. Lin *et al.* have demonstrated that a 3D tungsten PC can emit light effectively at a wavelength ~ 1.5 μm [6]. The large PBG in the mid-infrared range has ability to suppress the thermal emission from the 3D PC because of the trap of light in the PC region. At band edge, the flat dispersion relation predicts the slow group velocity of light and a longer light-matter interaction time. As a result, the intrinsic absorption by metal is enhanced in that wavelength range, leading to high efficiency of thermal emission.

Fig. 7 shows the schematic diagram of thermal emission setup. The four-layer titanium PC is supported by a 3.5-cm-long ceramic post for thermal isolation, and placed in a vacuum chamber pumped to ~ 5×10^{-5} Torr. A SiC heater below the sample is used for heating. In vacuum, no other gas would be heated to contribute unwanted signals. A probe of a thermocouple is placed close to the SiC heater. The temperature of the sample is defined as that of the SiC heater in vacuum. The thermal radiation from the sample is transferred from a point source to parallel light by a parabolic mirror and fed into the FTIR spectrometer. Fig. 8 shows the measured thermal emission spectra of the four-layer titanium PC at different temperatures. As temperature is raised, the total radiation power from the sample increases. The main emission peak is fixed at a wavelength of 3.5 μm for different temperatures, which is slightly different from the intrinsic absorption peak of titanium at a wavelength near 3.0 μm. At 636 K, the emission has a full width at half maximum (FWHM) of ~ 1.2 μm. This may be attributed to intrinsic absorption by titanium and enhancement by little the PBG effect near the band edge.

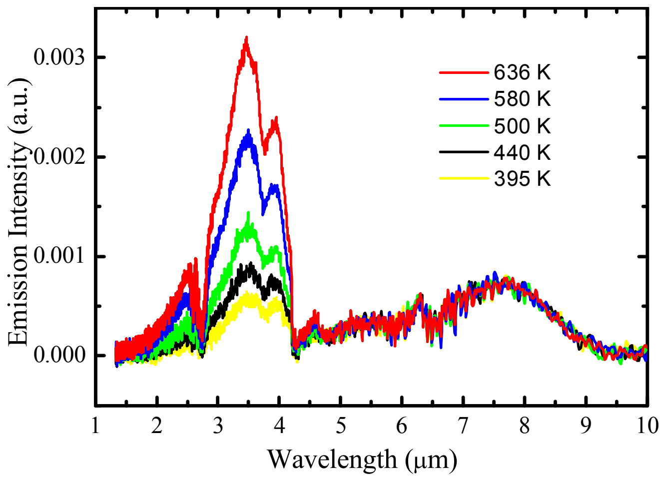


Fig. 8 Measured thermal emission spectra of the four-layer titanium PC at different temperatures. The dip at a wavelength of 2.8 μm is caused by the absorption of CO_2 in the environment.

4. CONCLUSION

In summary, the 3D titanium PCs with 100-nm feature sizes have been fabricated with the mature IC technology. The PBG effect of PCs is examined by measurement of reflectance spectra at normal and grazing incidence, and these measured results are verified by the 3D FDTD method. For the stacking direction of the 3D PC, the band edge locates at a wavelength of 5 μm. It is found that the optical behavior of p-polarized light in 3D titanium PCs dominates the range of complete band gap. Furthermore, the thermal emission spectra of the 3D titanium PC are measured at different temperatures. The emission peak at a wavelength of 3.5 μm with a FWHM of 1.2 μm is observed.

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