Infrared spectrally selective low emissivity from Ge/ZnS one-dimensional heterostructure photonic crystal

Weigang Zhang*, Guoyue Xu, Jianchao Zhang, Huihui Wang, Haili Hou

College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Jiang Jun Road 29, Nanjing 211106, China

ARTICLE INFO

Article history:
Received 14 April 2014
Received in revised form 18 June 2014
Accepted 20 June 2014
Available online 12 July 2014

Keywords:
Infrared emissivity
Spectrally selective
One-dimensional heterostructure photonic crystal
Optical coating technology

ABSTRACT

Ge/ZnS one-dimensional heterostructure photonic crystal (1DHPC) was successfully prepared by alternating thin films of Ge and ZnS on the quartz substrate by using the optical coating technology. The microstructure and spectral emissivity of as-prepared 1DHPC were characterized by using scanning electron microscopy (SEM) and fourier transform infrared spectrometer (FTIR), respectively. The test result of spectral emissivity shows that the average emissivities of as-prepared Ge/ZnS 1DHPC in the atmospheric windows of 3–5 μm and 8–14 μm can be as low as 0.046 and 0.190, respectively, but the average emissivity in the non-atmospheric window of 5–8 μm can be as high as 0.579. The results indicate that the as-prepared Ge/ZnS 1DHPC has obviously infrared spectrally selective low emissivity characteristic, basically meets the requirements of our design. The as-prepared 1DHPC with infrared spectrally selective low emissivity is promising for use as a material to unify the infrared stealth and effective cooling of the aircraft.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Low infrared emissivity materials have been extensively studied with the potential application in military technology of protecting aircraft from infrared detection based on the atmospheric windows (3–5 μm and 8–14 μm) [1–4]. In the past decade, several kinds of low infrared emissivity materials such as core–shell composites [5], multilayer structures [6], and nano-composite films [7,8] have been developed. Especially, the resin/metal composite coatings such as resin/Al and resin/Cu composite coatings have received extensive attentions due to their lower infrared emissivity and good mechanical properties for engineering applications [9,10]. However, all of the above materials do not have infrared spectrally selective low emissivity characteristic, they have low emissivities both in the atmospheric windows and non-atmospheric windows. As we all know, the external heat transfer in a high altitude environment of aircraft used mainly by thermal radiation, but low infrared emissivity may affect the efficiency of heat radiation. Therefore, it is hard to unify the infrared stealth and effective cooling of the aircraft using the traditional low infrared emissivity materials. In order to overcome the drawback of the above low emissivity materials, it is important to develop infrared spectrally selective low emissivity materials which have low emissivities in the atmospheric windows to achieve infrared stealth and high emissivities in the non-atmospheric windows to achieve effective cooling for the aircraft.

One-dimensional photonic crystals (1DPCs) are always periodic stacked by two dielectric materials with different refractive indices. The strong reflection peak in a specific wavelength range of 1DPC is revealed by Lord Rayleigh in 1887. One-dimensional heterostructure photonic crystals (1DPCs) are composed of two kinds of 1DPCs with different lattice constants. They can show two strong reflection peaks in two specific wavelength ranges [11,12]. These characteristics of 1DPCs may help us design infrared spectrally selective low emissivity materials [13]. In addition, photonic crystals can achieve excellent heat radiation performance by adjusting the photonic band gap [14–16]. Therefore, 1DPC is expected to unify the infrared stealth and effective cooling of the aircraft.

According to the Kirchhoff’s law [17] and Principle of Conservation of Energy, the relationship between the infrared emissivity (ε), reflectivity (r), and transmittance (t) can be expressed as: ε = 1 − r − t. But in this paper, due to the 1DPC consists of at least 12 layers, the transmittance is very small, so the infrared emissivity can be approximately expressed as: ε = 1 − r. Revealing that the reflectivity has a decisive effect on the infrared emissivity of 1DPC. According to these features, infrared spectrally selective low emissivity materials can be designed inspired from the 1DPCs.
In this paper, Ge/ZnS 1DHPC was designed and prepared by optical coating technology. Optical coating technology always used in aerospace, medical, and military applications, specializing in antireflection, hot and cold mirrors, and beamsplitter, using high vacuum deposition techniques. The effects of refractive index difference between the high and low refractive index dielectric materials, and the number of periods on the infrared emissivity of 1DHPC were systematically analyzed. The microstructure and spectral emissivity of as-prepared 1DHPC were systematically investigated.

2. Experimental

2.1. Materials

Ge particles (purity 99.999 wt%) and ZnS particles (purity 99.99 wt%) were purchased from Nanjing Sidier Paint Limited Company, China. All reagents were analytical grade and were used as received without further treatment.

2.2. Preparation of the 1DHPC

Quartz substrate (surface roughness 10 nm, diameter 5 cm, thickness 1 mm), properly cleaned by ultrasonic bath, was used as the substrate to prepare the 1DHPC. Then the 1DHPC was fabricated by alternating thin films of Ge and ZnS on the quartz substrate by optical coating machine (OTFC-900). Pure Ge particles and ZnS particles were pressed into billets as targets. The target-to-substrate distance was 60 cm. During the whole deposition process, the deposition rates of Ge layer and ZnS layer were 0.4 nm/s and 0.6 nm/s, respectively, the substrate temperature was maintained at 250°C, the chamber pressure 0.9 × 10⁻⁵ Pa, the accelerating voltage and current were 6 kV and 24 mA, respectively.

2.3. Characterization

The Photographs of the quartz substrate and 1DHPC were recorded by Nikon digital camera (COOLPIX22). The morphology and microstructure of the 1DHPC were observed by field emission scanning electron microscopy (S-4800). The sample was sputtered with a thin layer of Au prior to imaging. The normal spectral emissivity at the wavelength of 3–18 μm of the 1DHPC was measured by fourier transform infrared spectrometer (JASCO FTIR-6100). The Landcal R1500T blackbody furnace was used as the near-blackbody source. The normal spectral emissivity is the ratio of the radiance of a sample to that of a blackbody at the same temperature level and for the same spectral and normal directional conditions.

Table 1

<table>
<thead>
<tr>
<th>Samples</th>
<th>High refractive index layer thickness (μm)</th>
<th>Low refractive index layer thickness (μm)</th>
<th>Average emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3–5 μm1DPC</td>
<td>8–14 μm1DPC</td>
<td>3–5 μm1DPC</td>
</tr>
<tr>
<td>Ge/ZnS</td>
<td>0.250</td>
<td>0.688</td>
<td>0.455</td>
</tr>
<tr>
<td>Ge/ZnSe</td>
<td>0.250</td>
<td>0.688</td>
<td>0.410</td>
</tr>
<tr>
<td>ZnSe/ZnS</td>
<td>0.410</td>
<td>1.127</td>
<td>0.455</td>
</tr>
</tbody>
</table>

Fig. 1. Calculated reflection spectra of 1DHPCs designed by different dielectric materials with different refractive index differences in 5 periods.

Fig. 2. Calculated reflection spectra of Ge/ZnS 1DHPCs with different numbers of periods.

Table 2

<table>
<thead>
<tr>
<th>Number of periods</th>
<th>Average emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3–5 μm</td>
</tr>
<tr>
<td>4</td>
<td>0.171</td>
</tr>
<tr>
<td>5</td>
<td>0.141</td>
</tr>
<tr>
<td>6</td>
<td>0.130</td>
</tr>
</tbody>
</table>

Fig. 3. Microstructure model of 1DPC with infrared spectrally selective low emissivity.
3. Results and discussion

3.1. Theoretical analysis and design of the 1DHPC

The reflection spectra of 1DHPC can be calculated by using the characteristic matrix method for multilayer structure [18]. In order to make the 1DHPC has the maximum reflection peak intensity under the same conditions, we designed the optical thicknesses (the product of the layer thickness and refractive index of the corresponding dielectric material) of the two dielectric layers are equal to a quarter of center wavelengths (4 \( \lambda \)m and 11 \( \lambda \)m) of the reflection peaks [18]. Then the effects of refractive index difference between the high and low refractive index dielectric materials, and the number of periods on the reflection peak intensity of 1DHPC were systematically investigated in this paper.

In order to investigate the effect of refractive index difference between the high and low refractive index dielectric materials on the infrared emissivity of 1DHPC. Three kinds of 1DHPCs of Ge/ZnS, Ge/ZnSe, and ZnSe/ZnS both with 5 periods were designed by using Ge (refractive index 4.0), ZnS (refractive index 2.2), and ZnSe (refractive index 2.44) as film-based materials. The dielectric layer thicknesses of 1DHPCs are listed in Table 1. Fig. 1 shows the calculated reflection spectra of 1DHPCs designed by different dielectric materials with different refractive index differences in 5 periods. It can be seen that the refractive index difference between the high refractive index layer and the low refractive index layer has important influence on the reflection peak intensity and bandwidth. The photonic bandwidth becomes wider and the intensities of the peaks grow with increasing the refractive index difference between the high refractive index layer and the low refractive index layer, leading to the reflectivity and infrared emissivity both at the wavelength of 3–5 \( \mu \)m and 8–14 \( \mu \)m become larger and lower, respectively. The calculated infrared emissivities of the three kinds of 1DHPCs are listed in Table 1. It can be seen that the 1DHPC designed by using Ge layer and ZnS layer as the high refractive index layer and the low refractive index layer, respectively, has the lowest infrared emissivity both at the wavelength of 3–5 \( \mu \)m and 8–14 \( \mu \)m under the same conditions.

Fig. 2 shows the calculated reflection spectra of Ge/ZnS 1DHPCs with 4–6 periods. It can be seen that the intensities of the reflection peaks both at the wavelength of 3–5 \( \mu \)m and 8–14 \( \mu \)m grow slightly with increasing the number of periods from 4 to 6. Leading to the average emissivities at the wavelength of 3–5 \( \mu \)m and 8–14 \( \mu \)m decreased slightly from 0.171 to 0.130 and 0.192 to 0.147, respectively, and always kept at low values (Table 2). Considering the cost and process complexity to prepare the 1DHPC, we designed the number of periods was 5 for Ge/ZnS 1DHPC.
Integrating the above analysis and discussion, we finally designed the 1DHPC as shown in Fig. 3 to achieve the infrared spectrally selective low emissivity.

3.2. Microstructure and infrared emissivity property of the 1DHPC

The Ge/ZnS 1DHPC according to the structural characteristics of Fig. 3 was successfully prepared by using the optical coating technology (Fig. 4(b)). Fig. 5(a) shows the cross-sectional scanning electron microscopy (SEM) image of the Ge/ZnS 1DHPC with 5 periods, from which we can see the multilayered structure of the 1DHPC, and it is composed of 3–5 μm low emissivity 1DPC and 8–14 μm low emissivity 1DPC with lattice constants of 0.69 μm and 1.92 μm, respectively. The partial enlarged images (Fig. 5(b) and (c)) illustrate that the as-prepared 1DHPC is stacked by alternating thin films of Ge and ZnS on the quartz substrate, the thickness of the same dielectric layer is uniform in the 1DPC with the same lattice constant. Both of the two dielectric materials of 3–5 μm low emissivity 1DPC (Fig. 5(b)) and 8–14 μm low emissivity 1DPC (Fig. 5(c)) contain five layers. The average thicknesses of Ge layer and ZnS layer of the former are 0.27 μm and 0.42 μm, respectively, and the average thicknesses of Ge layer and ZnS layer of the latter are 0.71 μm and 1.21 μm, respectively, which basically agree with the thicknesses we designed (the former 0.25 μm and 0.455 μm, the latter 0.688 μm and 1.25 μm, respectively).

Fig. 6 shows the normal spectral emissivity at the wavelength of 3–18 μm of Ge/ZnS 1DHPC with 5 periods. It can be seen that the average emissivities of as-prepared Ge/ZnS 1DHPC in the atmospheric windows of 3–5 μm and 8–14 μm can be as low as 0.046 and 0.190, respectively, but the average emissivity in the non-atmospheric window of 5–8 μm can be as high as 0.579. The results indicate that the as-prepared Ge/ZnS 1DHPC has obviously infrared spectrally selective low emissivity characteristic, basically meets the requirements of our design.

4. Conclusions

In summary, Ge/ZnS 1DHPC with infrared spectrally selective low emissivity was designed according to the systematically theoretical analysis of the influencing factors of dielectric layer thickness, refractive index difference between the high and low refractive index dielectric materials, and the number of periods. Then the 1DHPC was successfully prepared by using the optical coating technology. The as-prepared Ge/ZnS 1DHPC has low infrared emissivity in the atmospheric windows of 3–5 μm and 8–14 μm, but high infrared emissivity in the non-atmospheric window of 5–8 μm. The low emissivity in the atmospheric windows can achieve infrared stealth, and high emissivity in the non-atmospheric window can achieve effective cooling for the aircraft.

Acknowledgement

This work was financially supported by the National Natural Science Foundation of China under Grant No. 51173079.

References

学霸图书馆
www.xuebalib.com

本文献由“学霸图书馆-文献云下载”收集自网络，仅供学习交流使用。

学霸图书馆（www.xuebalib.com）是一个“整合众多图书馆数据库资源，提供一站式文献检索和下载服务”的24小时在线不限IP图书馆。
图书馆致力于便利、促进学习与科研，提供最强文献下载服务。

图书馆导航：
- 图书馆首页
- 文献云下载
- 图书馆入口
- 外文数据库大全
- 疑难文献辅助工具