Vol 16 No 6, June 2007
1009-1963/2007/16(06)/1704-06
Chinese Physics
© 2007 Chin. Phys. Soc.
and IOP Publishing Ltd

Thin film design for advanced thermochromic smart radiator devices*

Feng Yu-Dong(冯煜东)[a)b)], Wang Zhi-Min(王志民)[b)],
Ma Ya-Li(马亚莉)[c)], and Zhang Fu-Jia(张福甲)[a)†]

[a)] *Physics Department, Lanzhou University, Lanzhou* 730000, *China*
[b)] *National Key Laboratory of Surface Engineering, Lanzhou Institute of Physics, Lanzhou* 730000, *China*
[c)] *National Key Laboratory of Vacuum and Cryogenics Technology, Lanzhou Institute of Physics, Lanzhou* 730000, *China*

(Received 11 November 2006; revised manuscript received 7 January 2007)

This paper describes the research on the materials and design methods for advanced smart radiator devices (SRDs) on large-area flexible substrates utilized on spacecraft. The functional material is thermochromic vanadium dioxide. The coating design of SRD is similar to the design of broadband filter coatings in a mid-infrared region. The multilayer coatings have complex structures. Coating materials must be highly transparent in a required spectrum region and also mechanically robust enough to endure the influence from the rigorous environments of outer space. The number of layers must be very small, suitable for the deposition on large-area flexible substrates. All the coatings are designed initially based on optical calculation and practical experience, and then optimized by the TFCALC software. Several designs are described and compared with each other. The results show that the emittance variability of the designed SRDs is great than 400%, more advanced than the reported ones.

Keywords: optical design, thermochromic, vanadium dioxide, smart radiator device
PACC: 4280X, 8760F, 9480

1. Introduction

The temperature of a satellite must be controlled according to the requirements for payload and platform. This is of crucial importance for a successful mission. Reducing the launch cost is one of the large development drives, for the launch cost is approximately proportional to satellite mass.[1] There is an increasing tendency to develop miniaturized satellites. Many conventional thermal control systems have turned out to be too bulky or heavy for these small spacecraft, thus functional surfaces are of great interest for the space industry. The smart radiator device (SRD) based on VO_2 films is one of most important structures of the functional thermal control surfaces, being lighter, more advanced and without moving devices.[2−4]

A large portion of the heat exchange between an object in space and the environment is performed through radiation, which is in turn determined solely by the object surface properties. The modulating device is attached to the object surface and thus provides a thermal window that can adapt to the changing conditions in orbit. The key material property is called thermochromism, which means that the material can adjust the infrared emittance automatically with temperature varying.

This paper presents such a surface, a thermochromic device with inorganic thin films based on VO_2 films for modulation of radiation at infrared and optical wavelengths. The solar absorptance and infrared emittance must be simultaneously determined. Furthermore, the design parameters including the sequence and thickness of the multiplayer materials must be optimized. An important aspect of designing the modern multilayer films is to use computers to match the multilayer parameters to a set of optical specifications such as a desired reflectance curve.[5,6] In the remainder of this paper, we briefly introduce the design process of multilayer films with the desired thermal radiative properties. The calculated thermal radiative properties of the SRD with the designed multilayer films are also presented. According to the design, the multilayer films are deposited by using the pulsed dc magnetron sputtering.

*Project supported by the National Natural Science Foundation of China (Grant No 60676033).
†Corresponding author. E-mail: Prof_zhangfj@sina.com

2. Calculation of emittance and absorptance

For an opaque coating, the spectral absorption $A(\lambda) = 1 - R(\lambda)$, while for a semitransparent coating, it is given by $A(\lambda) = 1 - R(\lambda) - T(\lambda)$, where $R(\lambda)$, and $T(\lambda)$ are the reflection and the transmission, respectively. $A(\lambda)$, $R(\lambda)$ and $T(\lambda)$ are functions of wavelength. The solar absorptance (α_s) and the infrared emittance (ε) can be calculated by weighting the measured spectral absorption with the incoming solar radiation $S(\lambda)$ and the blackbody spectrum $B_T(\lambda)$ (see Fig.1) for the valid temperature, and integrating over a particular wavelength interval.

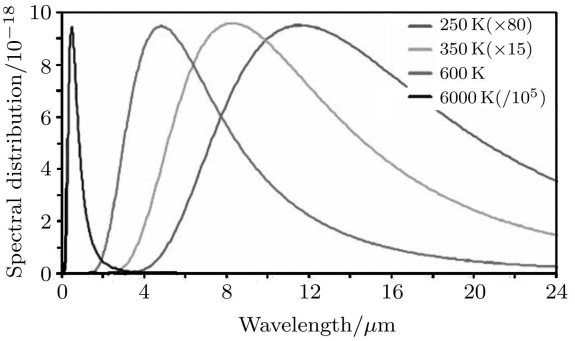


Fig.1. The normalized blackbody spectra at different temperatures.

The used weight function $S(\lambda)$ is a solar intensity distribution[7] (at an air mass of 1.5). The solar radiation approximates to $B_T(\lambda)$ at the surface temperature of the sun (ca. 6000 °C). The α_s and the ε are obtained from

$$\alpha_s = \frac{\int_{0.3\mu m}^{2.5\mu m} [1 - R(\lambda) - T(\lambda)] S(\lambda) d\lambda}{\int_{0.3\mu m}^{2.5\mu m} S(\lambda) d\lambda},$$

$$\varepsilon = \frac{\int_{2\mu m}^{50\mu m} [1 - R(\lambda) - T(\lambda)] B_T(\lambda) d\lambda}{\int_{2\mu m}^{50\mu m} B_T(\lambda) d\lambda}.$$

In this study the emittance refers to the directional one, since it is obtained from the above expression using reflectance data at an angle of incidence. It is an approximation to the hemispherical emittance that should be used for the thermal radiation of a satellite. If the emittance is calculated according to the above expression, the important thing that should be done is describe the wavelength range used. The error due to the long wavelength edge cut-off (e.g. Fourier transform infrared spectroscopy is often limited to about 25 μm) will be significant if the sample is at −50 − +25 °C, which are not unlikely temperatures on the outer wall of a satellite in orbit.

3. Choice of materials for multilayer films

3.1. VO_2 material

VO_2 material is a functional material for the thermochromic multilayer thin film SRD. It is also a good thermochromic material with significant changes in the crystallographic structure, and corresponding electrical and optical characteristics in response to external stimuli such as temperature, electric field and/or optical control signal.

The metal-insulator transition in VO_2 is associated with a change in structure from a monoclinic structure below the transition temperature (T_c) to a tetragonal rutile structure above the transition temperature.

Additional dopants, M, such as Ti and W, can be used to shift the transition temperature and tailor the resulting dynamic thermo-optic characteristics. For example, appropriate W and Ti dopants can tailor the transition temperature relative to the intrinsic value of about 68 °C over a wide range from below −30 °C to above 70 °C.[2]

The optical properties are studied extensively.[8−10] The optical constants for the IR region are given by Guinneton *et al*,[10] as shown in Fig.2.

3.2. IR transparent materials

A set of documents describing the relevant practical materials has been built up for space usage at Lanzhou Institute of Physics, China. Dielectrics, plastics and metals have all been used in spacecraft coatings with their optical properties documented. Bulk data may not be used to describe thin-film materials, because thin-films and their corresponding bulk materials normally are different in both packing density and crystalline structure, which results in their different refractive index and absorption features.

Spacecraft SRD coatings require dielectric materials to be highly transparent in a desired spectrum region. The chosen materials are some oxides, like

SiO_2, Al_2O_3, TiO_2, ITO; fluorides, like MgF_2, BaF_2; and semiconductor materials used for IR, like Ge, Si, ZnS, PbTe, etc. In order to be compatible with sputtering deposition on large-area flexible substrates, the optimal options are just SiO_2, Al_2O_3, TiO_2, Ge, Si, etc.

It is well known that these oxides do not have good transparencies in a far infrared region, especially an IR region for wavelengths longer than 10 μm. So the oxides cannot be used in general. Ge is a good IR transparent material, but has a large absorptance in a range of short wavelengths of solar radiation.

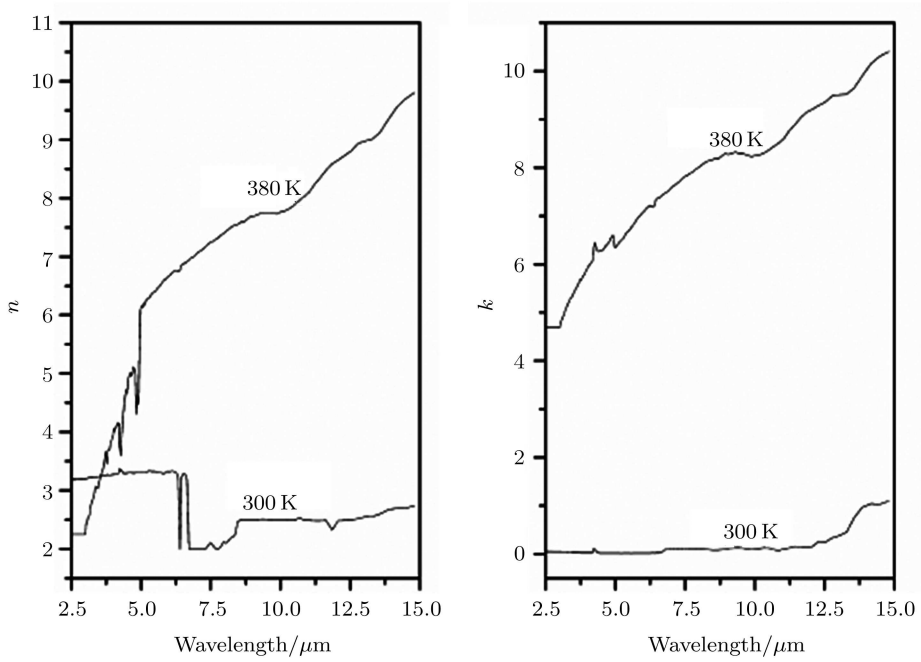


Fig.2. Optical index (n) and extinction coefficient (k) versus wavelength of the thermochromic VO_2 for $T = 380$ and 300 K.

3.3. Antistatic coating materials

Spacecraft run in the environments of space plasma, the surface of spacecraft accumulates static electricity easily and heavily and then the electrostatic discharge (ESD) will occur. ESD can destroy the SRD, even the whole spacecraft. In order to eliminate the ESD effects, the outer surface of the SRD must be electrically conductive. The optimal antistatic materials are indium tin oxide (ITO) and Ge coatings, which are also good materials against atomic oxygen in a low orbit.

4. Design

4.1. Conventional design of thermochromic SRDs based on VO_2

Figure 3 shows a simple structure of thermochromic SRD,[2] in which the VO_2 film is deposited on the aluminium surface of aluminized substrate. α_s is about 0.25, $\Delta\varepsilon$ about 0.35, and $\Delta\varepsilon/\varepsilon$ about 140%.

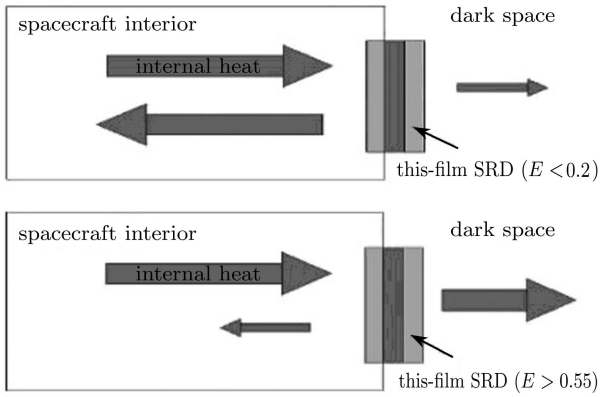


Fig.3. Simple structures of passive thermochromic SRDs based on VO_2 with different values of emittance E.

Figure 4 shows an improved structure for passive thermochromic and active electrochromic SRDs based on VO_2.

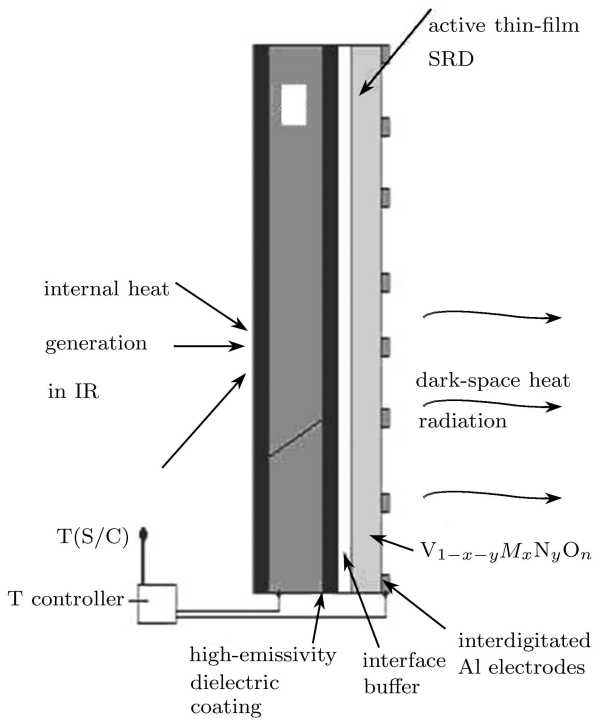


Fig.4. Improved structure for passive thermochromic and active electrochromic SRDs based on VO_2.

The structure has high-emissivity dielectric coating/Al/high-emissivity dielectric coating/VO_2/ITO. When running in a passive thermochromic mode, the $\Delta\varepsilon/\varepsilon$ is quite small (see Table 1).[3] When running in an active electrochromic mode, the $\Delta\varepsilon/\varepsilon$ is relatively large. $\varepsilon = 0.75 \pm 0.05$ when the voltage is lower than 2 V, $\varepsilon = 0.3 \pm 0.05$ when the voltage is larger than 5 V, and $\Delta\varepsilon$ is about 0.4, $\Delta\varepsilon/\varepsilon$ about 133%.[2]

Table 1. Preliminary emissivity (ε) measurements of passive thin-film SRDs based on VO_2

Sample No.	$\varepsilon(T < T_c)$	$\varepsilon(T < T_c)$	$\Delta\varepsilon$	$(\Delta\varepsilon/\varepsilon)/\%$
1	0.45	0.72	0.27	60
2	0.32	0.58	0.26	81.25
3	0.29	0.54	0.25	86.2
4	0.23	0.48	0.25	108

4.2. Ideal Multilayer film SRD

If there exists a kind of material(H) with a high transparency between ultraviolet and far infrared spectra, an ideal Multilayer film SRD can be designed. In the design, the ideal material is chosen to be Al_2O_3, but it has a good transparency in the infrared region. The refractive index (n) and extinction coefficient (k) are assumed to be 1.7 and 0 respectively. The designed film structure adopts a substrate of Al_2O_3/Ag/Al_2O_3/H/VO_2/H/VO_2/H/Ge, and the designed optical reflectance is shown in Fig.5. The solar absorptance α_s and thermal emittance are calculated. α_s is about 0.37, and ε changes dramatically, $\Delta\varepsilon$ is about 0.8, $\Delta\varepsilon/\varepsilon$ about 1500% (see Fig.6).

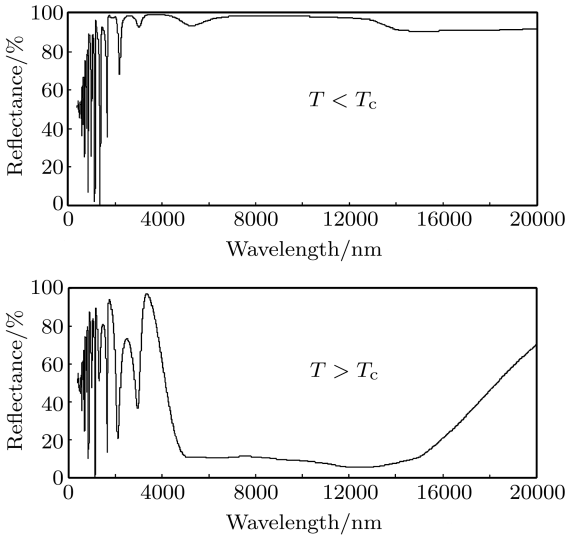


Fig.5. Optical reflectance of ideal multilayer film SRD.

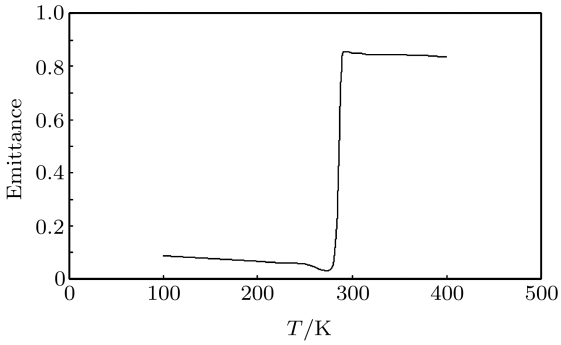


Fig.6. Emittance of ideal multilayer film SRD vs temperature.

4.3. Multilayer film design based on metallic oxide

The above ideal design seems to be encouraging, but unfortunately the ideal material is nonexistent. Among many metallic oxides, TiO_2 is the most interested material due to its durability in space environments and a wide transparent region (0.4–12 μm). A design based on TiO_2 is performed and further, optimized. The structure of multilayer films adopts a substrate of Al_2O_3/Ag/Al_2O_3/TiO_2/VO_2/TiO_2/VO_2/TiO_2/Ge.

The designed optical reflectance is shown in Fig.7. The solar absorptance α_s and thermal emittance are

calculated. α_s is about 0.4, and ε has a small change, $\Delta\varepsilon$ is about 0.5, $\Delta\varepsilon/\varepsilon$ about 130% (see Fig.8).

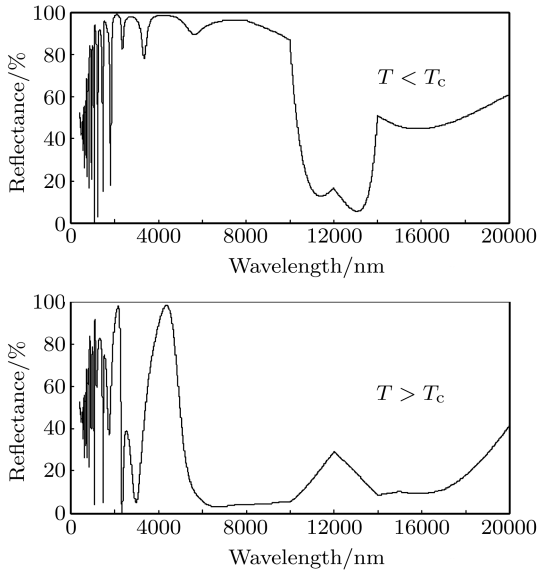


Fig.7. Optical reflectance of multilayer film SRD based on metallic oxides.

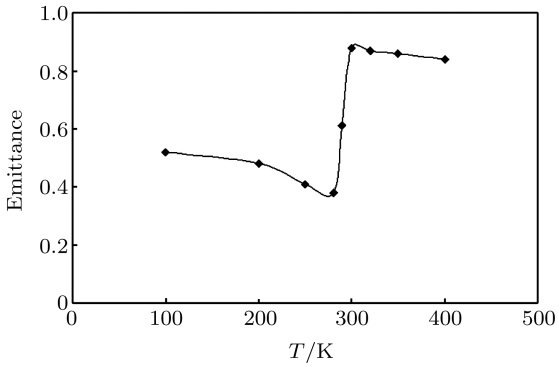


Fig.8. Emittance of multilayer film SRD based on metallic oxides versus temperature.

4.4. Multilayer film design based on Ge

Germanium is the most interested material in the IR region due to its durability in space environments and a wide transparent region (2–23 μm). A design based on Ge is carried out and, further optimized. The structure of multilayer films utilizes a substrate of Al_2O_3/Ag/Al_2O_3/Ge/VO_2/Ge/VO_2/SiO_2/Ge.

The designed optical reflectance is shown in Fig.9. The solar absorptance α_s and thermal emittance are calculated. α_s is about 0.44, and ε has a relatively large change, $\Delta\varepsilon$ is about 0.44, $\Delta\varepsilon/\varepsilon$ is larger than 400% (see Fig.10).

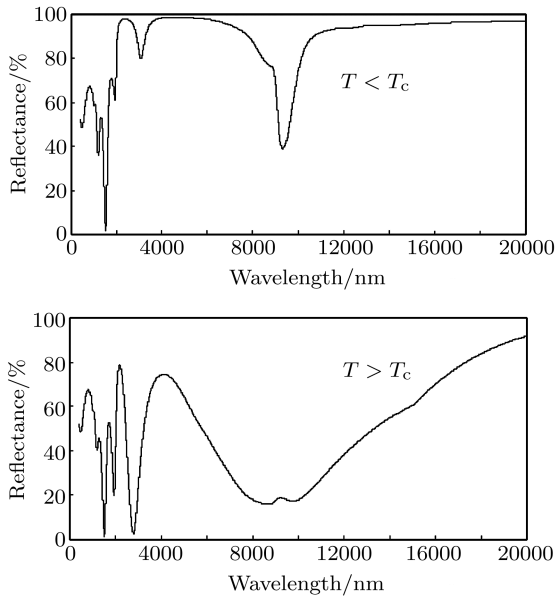


Fig.9. Optical reflectance of multilayer film SRD based on Ge.

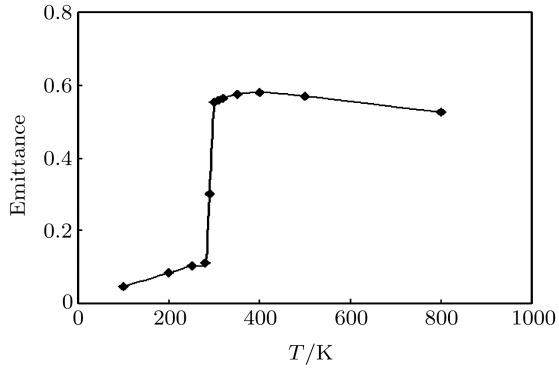


Fig.10. Emittance of multilayer film SRD based on Ge versus temperature.

5. Experiment and test of depositing multilayer film SRDs

VO_2 films are studied and deposited successfully by reactive pulsed-laser deposition[2] and reactive sputtering.[11,12] Ge, Al_2O_3, SiO_2 and VO_2 films are deposited separately in our laboratory by pulsed d.c. magnetron sputtering. The optical constants of Ge, Al_2O_3, SiO_2 and VO_2 films are measured, and the results show that all the measured data match the design data. The complete thermochromic SRDs based on Al_2O_3 are prepared. The results show that thermochromic SRDs based on Al_2O_3 are not a good option for advanced thermochromic SRDs as designed. The complete thermochromic SRDs based on Ge are in preparation.

6. Conclusion

Three kinds of thermochromic multilayer SRDs are designed and optimized. The results show that the ideal design is very encouraging, although the ideal material is nonexistent. It is a tendency to prepare more satisfactory thermochromic SRDs by finding more appropriate materials. The SRD based on metallic oxides is not good enough, but the thermal radiation property is better than that of traditional thermochromic SRD. The SRD based on Ge is perfect, it has a large emittance change, and $\Delta\varepsilon/\varepsilon$ being larger than 400%, which is much better than that of traditional thermochromic SRD.

References

[1] Wertz J R and Larson W J 1999 *Space Mission Analysis and Design* (Kluwer, Dordrecht)

[2] Haddad E, Kruzelecky R V and Jamroz W 2003 Dynamically-Variable Thin-film Smart Radiator Device, 4th Round Table on Micro/Nano Technologies for Space

[3] Nikanpour D 2003 *Smart Radiator Offering Autonomy in Satellite Thermal Control* (Canadian Space Agency)

[4] Kruzelecky RV, Haddad E, Jamroz W, Soltani M, Chaker M and Nikanpour D 2002 Integrated Thin-Film Smart Coatings with Dynamically-Tunable Thermo-Optical Characteristics, SAE Proceedings of the 32nd International Conference on Environmental Systems, San Antonio, Texas

[5] Li L and Dobrowolski J A 1992 *Appl. Opt.* **31** 3790

[6] Dobrowolski J A and Kemp R A 1990 *Appl. Opt.* **29** 2876

[7] International standard 1999 ISO/CIE 10526 CIE standard Colorimetric Illuminants

[8] CASE W E 1983 *Appl. Opt.* **22** 1832

[9] Chudnovskii F A, Pergament A L, Schaefer D A and Stefanovich G B 1981 *Optical medium on the basis of vanadium oxide films,* SPIE 2777

[10] Guinneton F, Sauques L, Valmalette J C, Cros F and Gavarri J R 2004 *Thin Solid Films* **446** 287

[11] Chen C H, Yi X J and Xiong B F 2001 *Chin. Phys.* **10** 450

[12] Wang X J, Fei Y J, Xiong Y Y, Nie Y X, Feng K A and Li L D 2002 *Chin. Phys.* **11** 737