Semiconductor Physics, Quantum Electronics & Optoelectronics, 2008. V. 11, N 2. P. 159-162.

PACS 41.81.Pa

Design of optical-electronic sensor for ablation of spacecraft heat protection

G. Hornostaev, V. Pasichny and Yu. Lytvynenko*
I. Frantsevich Institute for Problems of Materials Science, NAS of Ukraine
3, Krzhizhanovsky str., 03142 Kyiv, Ukraine
**E-mail: yurimlyt@mail.ru; phone: (38 044) 424-24-44, fax: (38 044) 424-21-31*

Abstract. Results of designing and studying the characteristics of the fiber-optic sensor for the ablation of the low-sublimating heat protection which intended for the use on the being got down module of article "Mars-5" are represented. The originality of development consists of guarantee for continuous measurement of the instantaneous value of thickness of heat protective coating of the article during its descent. Achieving this goal is ensured by the application of two light-guide sensors, one of which is made from color glass-light filter.

Keywords: heat protection, ablation, sensor, light guide.

Manuscript received 07.02.08; accepted for publication 15.05.08; published online 30.06.08.

1. Introduction

The large volume of developments for the creation of the optical-electronic means for monitoring the operating characteristics of the heat-proof materials used at the being got down spacecraft was carried out in the Institute for Problems of Materials Science, NAS of Ukraine.

This paper presents the first part of the studies devoted to the creation of a sensor for the continuous measurements of the thickness value for the ablated low-sublimating materials used at the being got down module "Mars-5" (customer is SIU "Energy", Russia [1, 2]).

These problems were posed with the development of the optical sensor of ablation on the basis of the measurement of the length of color light guide:

1) to ensure the independence of the sensor indications from both the external illumination and temperature of the being destroyed surface of heat-proof material;

2) to ensure the average accuracy of the order of several percentages when the length of the color light guide is being measured.

Light guides from the color glass were made in KS Scientific Research Institute, St.-Petersburg according to the technical task of Institute for Problems of Materials Science, NAS of Ukraine.

The first problem is solved by the way of using the bridge measuring circuit of voltage by two photodetectors, one of which is illuminated through the transparent while the second through the color light guide. The instrument must measure not the absolute illumination, but only relation of the illumination of photodetectors in both the transparent and color channels. The second problem is solved by the correct selection of photodetectors, material of light guides and by the filtration of input noise.

2. Procedure of measurement of the heat protection removal

It is necessary to introduce the characteristic named as the length constant Λ of a color light guide. Its light transmission is changed by e times with a change in the length of the light guide on the value Λ_t while the photoresistance illuminated through the light guide is changed also by e times with a change in the length of the light guide by the value Λ_p. We should measure a change Δ of the length of color light guide. If the resistance is measured with the accuracy of 3-5 %, then it is obvious that the minimum value of resistance under the entire light guide must also composes 3-5 % of the value of resistance under the light guide, which was burnt by the value Δ.

Consequently, the value of removal must exceed the length constant Λ_p from 3.5 ($e^{-3.5} = 0.03$) to 3 times ($e^{-3} = 0.05$). At a distance $\Delta = 2\,\Lambda_p$, instead of the exponential dependence of resistance on the length of light guide, it is possible to use the gross linear approximation, in which the deviation of exponential curve from the straight line does not exceed 10 % of the value Δ. For the practical use, it is necessary to select the color light guides, in which 2 or 3 length constants are placed in the assigned thickness of the layer of the heat protection removal.

The section of the light guide with the length of l_r remains after combustion yet. In order that the photodetectors under the transparent and color light guides would work in the same photoresistance range (so that a constant relation of resistances remains with this relation of the illuminations), it is necessary to compensate their illuminations introducing an additional filter into the channel of the transparent light guide. The compensating filter is selected in such a manner that its transmission would be equal to the transmission of the color light guide, which had burnt to have the length (l_r + 0.5 Δ). The matching of materials is executed for the thickness of the removal layer of approximately 10 mm with the use of photoresistance СФ3-1.

Transmission of the compensating filter is

$$\tau_F = \exp\left[\left(l_r + 0.5\Delta\right)/\Lambda_p\right].$$

The photosensitivity is defined as the value reversed to the energy of the luminous flux which is necessary for maintaining the constant value of photoresistance. The spectral sensitivity can be calculated from both the spectral effectiveness curve for the emissions of equal power and the dependence of the photoresistance on the power, which was measured for one of the wavelengths.

3. Studying the energy characteristic of the detector СФ3-1

The measurements of photoresistor with the strong light fluxes were carried out under the conditions of the concentration of the light beam from illuminator by a parabolic lens into the focal spot with a diameter of 4 mm. СФ3-1 characteristic in the average range of illumination was obtained in the monochromatic green as well in the visible light, whereas the IR part of the spectrum was cut off by the light filter SZS-28, at high illumination in the red and infrared regions of the spectrum (red filter) (Fig. 1). The illumination measurements were carried out by both the selenium photocell F-102 and the microammeter M-95.

The neutral grey filters NG-6, NG-8, NG-9, NG-10 with the identical absorption spectrum in the IR range but with different density were used for the work in the red – infrared regions. The following values were used for the calculations: the maximum of sensitivity of the selenium photocell of 556 nm; the energy flux of 1 lm/m^2 at the light wavelength λ = 556 nm are equal to 1.46×10^{-7} W/cm^2; the photosensitivity of the selenium photocell at the wavelength λ = 510 nm is 92 % of the maximum; photosensitivity СФ3-1 at the wavelength λ = 510 nm is equal to 2.5 % of the peak one. The data about the luminous flux are reduced to the peak of spectral sensitivity of СФ3-1 (λ = 720 nm).

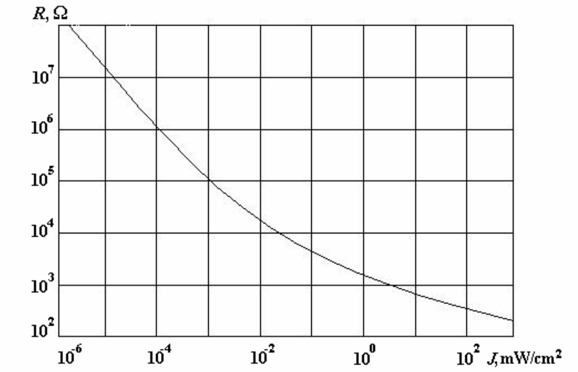

Fig. 1. Energy characteristics of СФ3-1: R – resistance, Ohm; J – flux density, mW/cm^2.

4. Study of the СФ3-1 spectral efficiency

The optical part of the spectrophotometer СФ-4 has been used as the luminous source with the following changes:

1) the quartz-halogen lamp КГЛ-12-100 with a power of 100 W is established in the illuminator. The lamp is delivered by the current of 8 A, with the voltage of 12.0 V from the rectifier stabilized by ferroresonant stabilizer C-0.5;

2) the glass lens with the focal length 60 mm, which forms in the focus the vividly illuminated square field with the size of 4×4 mm is established in the output window of instrument.

The adjustment of the wavelength scale was carried out with the aid of the monochromatic ray of helium-neon laser ЛГ-52 with the wavelength 632.8 nm. The absolute energy of the luminous flux was measured at the wavelength 556 nm (where the flux of 4.07××10^{15} quantum/(s·m^2) corresponds to illumination of 1 lx) by the luxmeter of Ю-16. The radiated power is 0.17 mW at this wavelength. The relative measurements of the radiated power described below make it possible to estimate the power with values to 2 mW in the infrared region.

The bolometer based on thermistors MMT-1 was used as the receiver of radiant energy. Measuring illuminated thermistor was smoked while the second thermistor, which compensated the changes of the general temperature of building, was closed with white screen. A change in the resistance under the radiant heating from the monochromator is small and consists of about 0.05-0.3 % of nominal. For the voltage amplification the operational amplifier whose output was measured by millivoltmeter is used.

The correction for convection drift was introduced as follows: output voltage U_0 before the opening the lock of monochromator was measured, then the voltage U_1 in t_1 = 30 s after beginning the illumination was measured. At once the lock was shut and after the time t_2 (1.0 min) the voltage U_2 with the unlighted bolometer was measured. The signal can be expressed as

$$U = U_1 - (U_2 - U_0)\, t_1/(t_1 + t_2).$$

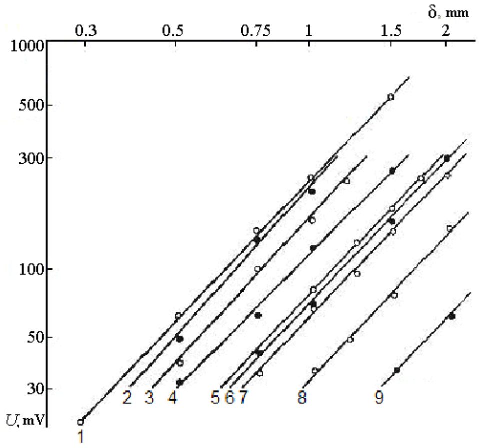

Fig. 2. Dependence of the potential U of the bolometer on the equal energy width δ of the monochromator slot for the different wavelengths of the emission: 1.0 (*1*), 1.25 (*2*), 1.5 (*3*), 0.9 (*4*), 0.8 (*5*), 1.75 (*6*), 0.7 (*7*), 0.6 (*8*), 0.5 μm (*9*).

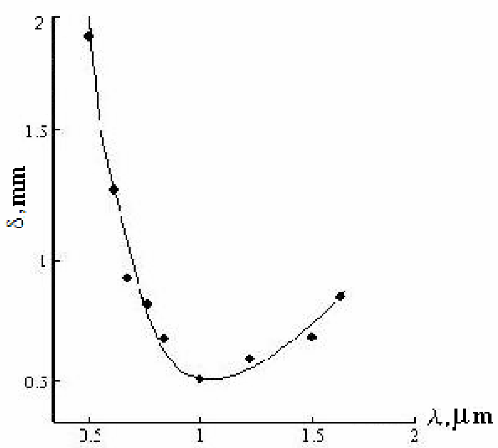

Fig. 3. Calculated equal energy width δ of the monochromator slot for the different wavelengths λ of emission.

The dependence of the radiation power on the width of the monochromator slot was obtained for 9 wavelengths (Fig. 2). Dependence between the logarithms of both the width of slot and the output voltage is strictly linear: the average coefficient of linear correlation is equal to 99.84. The average inclination of the dependence composes of 2.118 (Table). The obtained linear dependences can be used for the calculation of the slot width by the method of the least squares; so that the radiation power is retained at the level of unity with λ = 500 nm for the maximum disclosure of the slot (2 mm).

The dependence of the equal energy width of slot on the wavelength is shown in Fig. 3. The radiation power in the blue spectral region was insufficient to obtain the dependence described above. With the completely opened slot, the powers for λ = 450 nm and 425 nm were equal, respectively, 45 and 37 % of the emission with the wavelength of 500 nm. Extrapolation for 475 and 400 nm gives estimations which respect of 66 and 28 %. After establishing both the wavelength with a step of 25 nm and the appropriate width of slot for the flow of a constant power the lock was opened.

Table. The coefficient of linear correlation β and the inclination α of the dependence of the logarithm for the equal energy width δ of the monochromator slot on the output voltage *U* for various wavelengths λ.

λ, nm	600	700	800	900	1000	1250	1500	1750
β	99.79	99.89	99.94	99.84	99.98	99.57	99.74	99.88
α	2.129	2.084	2.129	2.036	2.109	2.246	2.146	2.063
δ, mm	1.291	0.964	0.863	0.699	0.490	0.553	0.603	0.899

In Fig. 4a, the values of the СФЗ-1 photodetector in the flow of equal power are shown for the different wavelengths, that is the curve of the spectral efficiency. According to the amplitude characteristic of the detector (Fig. 4b), we find a relative illumination which corresponds to the measured value of resistance. This relative illumination characterizes photosensitivity. The peak photosensitivity is accepted as 1.

5. The selection of glass for the color light guide

In accordance with the measured spectral characteristics of the photodetector СФЗ-1, the glass must have a passband within the range 700 to 800 nm. The length constant for the thickness of the removal layer of 10 mm must comprise from 3 to 5 mm. From the formula of the transmission coefficient of color glass

$$\tau = \left(10^{k_\lambda l - D}\right)^{-1},$$

where l is the length of color light filter, mm; k_λ is the decimal absorption coefficient for the layer of 1 mm;

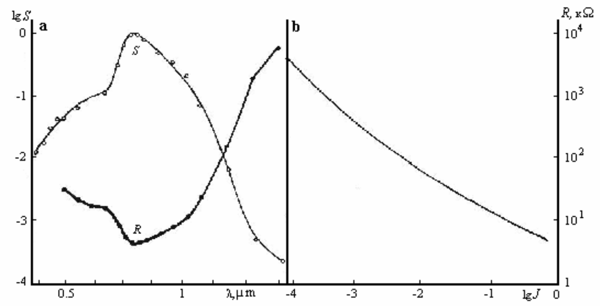

Fig. 4. The spectral sensitivity of the photodetector СФЗ-1: a – resistance R and photosensitivity S with the equal energy illumination; b – the amplitude characteristic of the photodetector, J – flux density.

D is a correction for reflection (value of the order of 0.04 for larger quantity of glasses), we find the absorption coefficient:

$k_\lambda = (1\mathrm{g}\ e + D)/\Lambda_t$.

With the value $\tau = l/e$ and $l = 3–5$ mm, the necessary value of k_λ composes of 0.160–0.095, respectively. According to State All-Union Standard (USSR) 9411-60 to the color glasses the NG-3 glass has the color optical characteristics which close to assigned ones.

6. Conclusions

The amplitude characteristic and spectral sensitivity of photodetector СФЗ-1 are investigated; the selection of the material of a color light guide is substantiated; initial data for creating the sensor of continuous ablation are obtained (results of its tests will be represented in the following paper).

References

1. G.F. Hornostaev, V.V. Pasichny and G.V. Tkachenko, Method of measurement by radiant component of heat flux on the surface of ceramic heat protection // *Kosmichna nauka i tekhnologiya,* **12**(2/3), p. 98-102 (2006) (in Ukrainian).
2. G.F. Hornostaev, V.V. Pasichny and G.V. Tkachenko, Methods of the control of operating characteristics of heat protection by the fiber-optic sensors // *Kosmichna nauka i tekhnologiya,* **13**(3), p. 12-18 (2007) (in Ukrainian).