CONTAMINATION OF QUARTZ GLASS SAMPLE SURFACES UNDER IRRADIATION BY OUTGASSED VOLATILE PRODUCTS

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ABSTRACT

Results of experimental simulation of deposition of spacecraft outer atmosphere products on high-orbit spacecraft optical surfaces are given. Basic data have been obtained when studying changes of quartz glass transmittance due to action of outgassed products of a polymeric composite and electron radiation.

1. INTRODUCTION

In spacecraft service conditions there occurs degradation of its optical materials, windows, lenses, photoelectronic device windows, etc. Major reasons why optical properties of high-orbit spacecraft skin materials change are, as a rule, action of space ionizing radiations [1-3] and their contamination by spacecraft outer atmosphere products [4-6].
An electron-hole plasma, which recombination causes emergence of radiation-induced color centers, accumulation of volume interstitial charge and appearance of radioluminescence, is generated together with the radiation-induced defects in optical materials under irradiations. While irradiating, the traps responsible for generation of color centers in material are filled up with electrons and electron vacancies that result in increase of optical density. Color centers are also generated in radiation-induced defects that are newly formed under the action of high-energy particles.
It is known that the cited effects cause both direct changes of optical properties of materials and growth of their contamination rate by spacecraft outer atmosphere products. Indeed, the radiation-induced defects become additional growth centers of islands of contamination films on material surface, and its electrization may stimulate deposition of volatile products.

2. EXPERIMENTAL RESULTS

Changes of optical properties of spacecraft skin materials in service conditions is mainly tied with radiation-induced color centers generating in the materials and with contamination of their surfaces by spacecraft outer atmosphere products. To find contribution of the first process in changes of transmittance quartz glass samples were subjected to ionizing radiation. Fig. 1 shows spectral transmittances (parameter T) of samples irradiated by 40-keV electrons. It is seen that increase of integral electron flux results in growth of quartz glass optical density (reduction of the parameter T). The necessity of these experiments was stipulated by the fact that when analyzing combined action of molecular flux (MF) and ionizing radiation one may subtract the radiation component and evaluate changes of transmittance directly linked with contamination of sample surfaces by outgassed products.

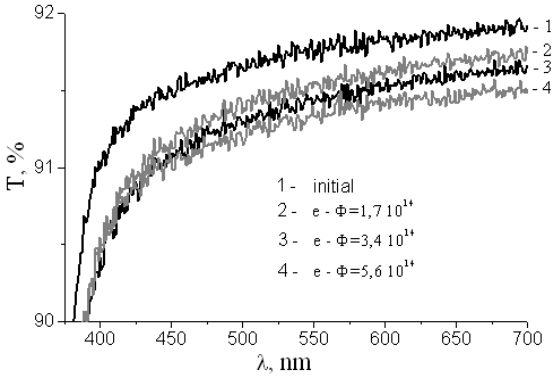

Fig. 1. Spectral transmittances of quartz glass samples irradiated by different electron fluxes (cm^{-2}): 1 – Φ=0; 2 – $\Phi=1.7\times10^{14}$; 3 – $\Phi=3.4\times10^{14}$; 4 – $\Phi=5.6\times10^{14}$

Measurements of spectral transmittances of quartz glass samples were carried out using the modern double-beam spectrophotometer «Cary 500» and 150-mm integrating sphere DRA-CA-55 mounted in measurement compartment. MF source and the table which the quartz glass samples are attached to, are maintained at the temperatures of 100 ± 1^0C and 20 ± 1^0C respectively.
Fig. 2 shows scheme of the experiments concerning influence of irradiation on deposition of volatile products (VP) being the MF components on surfaces of quartz glass samples attached to coolable table.
The polymeric composite EKOM-1 (spacecraft thermal control coating) with well-studied outgassing kinetics

and notorious molecular composition of outgassing VP was taken as the MF source.

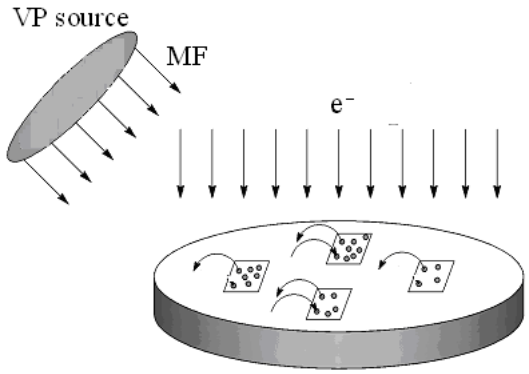

Fig. 2. Scheme of experiments on studying combined action of molecular flux and electron radiation on quartz glass samples

Fig. 3 shows results of combined action of MF and electron radiation on quartz glass samples. Initial electron energies and its fluxes were chosen to be coincided with ones used to find contribution of radiation component in changes of transmittance.

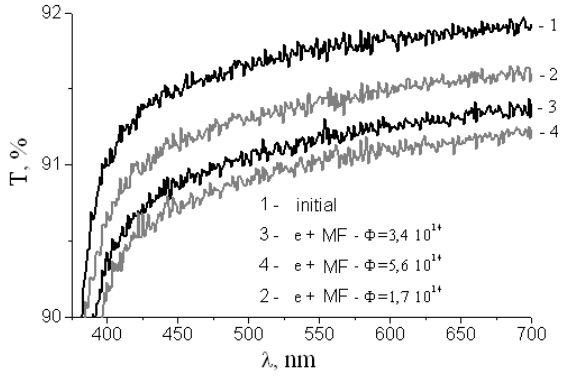

Fig. 3. Spectral transmittances of quartz glass samples after action of MF and different electron fluxes (cm^{-2}): 1 – Φ=0; 2 – $\Phi=1.7\times10^{14}$; 3 – $\Phi=3.4\times10^{14}$; 4 – $\Phi=5.6\times10^{14}$

Analysis of experimental data showed that simultaneous bombardment of samples by outgassed products and electrons brought to greater reduction of transmittances as compared with their separate action.

3. NUMERICAL ANALYSIS OF EXPERIMENTAL DATA

In general, efficiency of energy and mass exchanges between outgassed products and contaminatable solid substrate is defined by accommodation and condensing coefficients as well as adsorption probability. Hitting the solid surface the adsorbing molecules turned out to be in loosely-coupled states in which they diffuse over the surface until desorption occurs or when strong bonds make up.

Irradiation of quartz glass results in increase of number of defects on its surface where generation of nuclei forming the contamination film occurs. This takes place because the threshold energy of chemical adsorption on defects is less than elsewhere. Then islands of chemical adsorption expand around these nuclei. This is attributed to the fact that adhesion of molecules to periphery of these islands occurs easier as a result of lowered threshold energy that facilitates chemical adsorption. Threshold of the free energy needed to transfer from physically sorbed into chemisorbed state is significantly less near previously chemisorbed particles due to lateral attraction to them. This attraction can be tied with oscillatory indirect interaction between particles of adsorbed substance through electron subsystem of the substrate.

Thus, the chemical adsorption can be divided in three stages:

1) filling up the defective places;
2) expansion of islands of chemical adsorption around nuclei in defective places (this is an autocatalytic stage; the more particles are adjoined, the longer is the periphery and hence there will be more places with low threshold of chemical adsorption);
3) islands overlap.

To describe mathematically accumulation rate of outgassed products on quartz glass surface the mathematical model given in [7] is applied. It is postulated in the model that outgassing rate of *i*-type VP $dF_i(t)/dt$ from unit surface of a source is proportional to its concentration in the near-surface layer $C_i(h,t)$ at a time. In turn, deposition of outgassed products on substrate surface is considered as the result of several processes in it, and it is supposed that contamination rate is defined by properties of the surface itself and by molecular flux that hits it.

When studying contamination of quartz glass sample surfaces, VP flux hitting the samples at a given distance from the VP source was used. This MF can be found from:

$$F_{c\,total}(t) = \alpha_{cs} S_0 \sum_{i=1}^{N} \int_0^t \frac{dF_i(\tau)}{d\tau} \cdot d\tau = \\ = \alpha_{cs} S_0 \sum_{i=1}^{N} \int_0^t k_i C_i(h,\tau) d\tau, \qquad (1)$$

where k_i – effective desorption coefficient of *i*–type VP from VP source; h – thickness of VP source; S_0 – surface area of VP source; α_{cs} – geometric factor

depending on arrangement of VP source and quartz glass sample surface.
It can be calculated from:

$$\alpha_{cs} = \frac{1}{A_c} \int_{A_s} \int_{A_c} \frac{\cos\theta_c \cos\theta_s}{\pi r^2} dA_c dA_s, \qquad (2)$$

where θ_s (θ_c) – angle between the normal line to a surface element of VP source dA_s (to a substrate surface element dA_c) and the line uniting the element with the substrate surface element dA_c (with VP source surface element dA_s); r – distance between the surfaces.
Part of VP of MF is deposited on surface of glass samples. Here, $C_i(h,t)$ and rate of change of *i*–type VP mass $dM_{ci}(t)/dt$ on quartz glass surface that depends on condition and temperature of the surface as well as on composition, energy and state of charge of MF components are described as follows:

$$\frac{dM_{ci}(t)}{dt} = \alpha_{cs} S_0 k_i C_i(h,t) - k_{ci} M_{ci}(t) - \qquad (3)$$
$$- \chi_{ci}^{rad}(t) M_{ci}(t),$$

where k_{ci} – effective reemission coefficient of *i*–type VP from a sample surface;
$\chi_{ci}^{rad}(t)$ – chemical reaction rates with involvement of *i*-type MF component on substrate surface under radiation.
Chemical reaction rate on substrate surface under radiation can be expressed as:

$$\chi_{ci}^{rad}(t) = \chi_{ci}[\beta - \delta \exp(-\gamma t)], \qquad (4)$$

where χ_{ci} – chemical reaction rate with involvement of *i*–type VP on non-irradiated substrate surface when outgassed products hit it; β, δ and γ – parameters depending on type, spectrum and intensity of ionizing radiation exerting influence on a substrate, here $\beta - \delta = 1$.

The necessity to introduce time dependence of chemical reaction rates put in appearance as a result of study of experimental data that were similar to shown in Fig. 3 and derived from simultaneous and having different durations bombardment of quartz glass samples by molecular flux and electrons.
Total contribution of *i*–type VP into mass of outgassed products that have deposited on unit surface of quartz glass can be found from:

$$M_{ci}^{sum}(t) = M_{ci}(t) + \Delta_{ci}(t), \qquad (5)$$

where $\Delta_{ci}[t, \chi_i(t)]$ – mass of *i*–type VP that takes place in chemical reactions on quartz glass sample surface, or chemically adsorbed on it by time t:

$$\Delta_{ci}[t, \chi_i(t)] = \alpha_{cs} S_0 \int_0^t \frac{dF_i(\tau)}{d\tau} - M_{ci}(t) - \qquad (6)$$
$$- k_{ci} \int_0^t M_{ci}(\tau) d\tau$$

Action of high-intensive low-energy radiations on quartz glass can cause the temperature jump of material that, in turn, will intensify processes like VP surface diffusion and desorption. As an example, Fig. 4 shows calculated curves of VP accumulation on quartz glass surface at substrate temperatures of 40^0C (curve 4 *a*) and 60^0C (curve 4 *b*). Here is assumed that molecular fluxes come from the same VP source, that is they are of the same intensity.

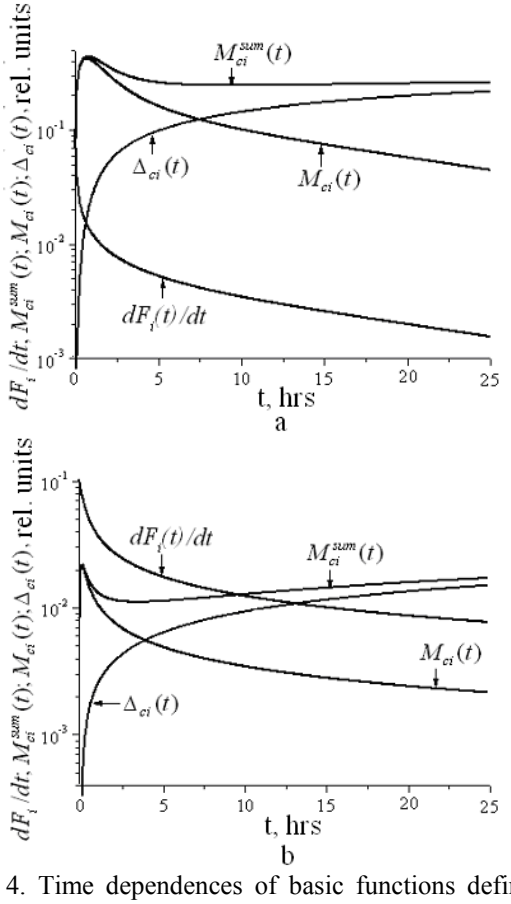

Fig. 4. Time dependences of basic functions defining VP accumulation on substrate surfaces at different temperatures: *a* – T= 40^0C; *b* – T= 60^0C

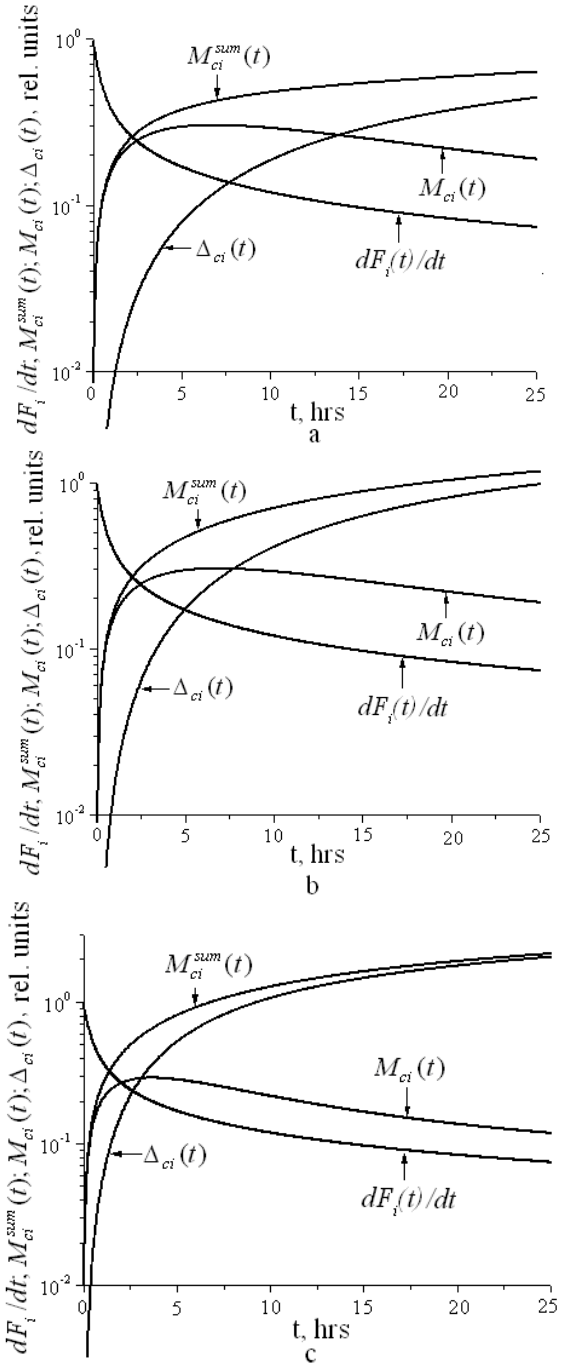

Fig. 5. Time dependences of basic functions defining VP accumulation on substrate surfaces: *a* – without irradiation; *b* – if considering (4); *c* – for constant parameter $\chi_{ci}^{rad} = \beta\chi_{ci}$

Fig. 5 gives time dependences of basic parameters defining accumulation of organic substances on a quartz glass surface maintained at 20^{0}C. $M_{ci}^{sum}(t)$, $M_{ci}(t)$, $\Delta_i(t,\chi_i)$ were calculated based on the above-mentioned mathematical model. To make comparative appraisal of radiation effect on contamination of sample surfaces by outgassed products, Fig. 5*a* shows calculation data for the case when only the molecular flux hits the surface of a model material.

Calculation data in Figs. 5*b* and 5*c* have significant differences. This can be explained in the following way. Time dependence of chemical reaction rate was taken into consideration in the first case; it was supposed that chemical reaction rate at initial moment of irradiation increases to a certain fixed value in a step-wise manner and then become time-independent in the second case. It is seen from the curves that allowance for (4) results in that mass of *i*–type VP (see $M_{ci}(t)$) accumulated on substrate surface over the observation period is 1.4 times greater as compared with the same characteristic obtained if this dependence is not taken into consideration. However, total mass of contamination film $M_{ci}^{sum}(t)$ calculated with due regard to (4) is half as much than in the case shown in Fig. 5*c*.

Study of experimental data showed that the model allowing for time dependence of chemical reaction rates is the one that describes most sufficiently accumulation of contamination film on quartz glass surface.

Increase of chemical reaction rates (involving within the boundaries of the given model the chemical adsorption as well) with involvement of *i*–type VP under combined action of MF and radiation on substrate surface gives rise to a more quick increase of contribution of these molecules $M_{ci}^{sum}(t)$ in total mass of forming organic film. Outgassing rates of VP source are the same for all cases. However, when the samples are subjected to combined bombardment by MF and electrons, $M_{ci}^{sum}(t)$ exceeds the same parameter for the case when only the outgassed products hit the quartz glass surface.

Thus, experimental and numerical simulation data have shown that action of low-intensity electrons ($\varphi < 5\cdot10^{10}$ $cm^{-2}\cdot s^{-1}$) causes increase of growth rate of organic film on quartz glass sample surfaces if subjected to outgassed products of polymeric composite.

Growth of deposition rate of outgassed products can be partly tied with the fact that when irradiating quartz glass by 40-kev electrons accumulation of space charge occurs in the near-surface layer (thickness of about 10-12 μm). Electric field of this distributed charge pulls the molecules ionized due to irradiation to sample surfaces. Electrization of quartz glass samples was not considered in this work.

4. CONCLUSIONS

Analysis of experimental data concerning study of irradiation effect on deposition of outgassed products of polymeric composite on quartz glass surface has shown that:

- action of electron radiation with intensity below 5×10^{10} $cm^{-2}\times s^{-1}$ on quartz glass samples results in growth of deposition rate of outgassed products on their surfaces, that is in increase of growth rate of contamination film;
- to analyze numerically and interpret experimental data one should use mathematical models describing contamination of optical surfaces by outgassed products with allowance for time dependencies of chemical reaction rates that take place on substrate surface.

When preparing to test and carrying on tests of optical materials of high-orbit spacecraft skin, authors recommend to take into account results of the work to predict changes of their spectral characteristics due to contamination caused by outer atmosphere products.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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