

# Changes of Solar Array Surfaces on Orbital Station Mir

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Several fragments (front and back protective glasses) of a solar array were investigated after its return from the orbital station Mir to Earth in 1998 after functioning in the low-Earth-orbit environment for 10.5 years. Three methods of surface analysis were applied: scanning electron microscopy, local x-ray microanalysis, and x-ray photoelectron spectroscopy. The main changes to solar array surfaces after prolonged exposition in low Earth orbit are caused by contamination layers (thicknesses up to 3  $\mu\text{m}$ ) that deposit from the intrinsic outer atmosphere of the station. Besides contamination deposits, some surface damages are observed (dimensions of 5–20  $\mu\text{m}$ ), caused by micrometeoroid and/or debris impacts. The outer layers of the contamination deposits consist of spheroid particles with dimensions of 0.3–0.5  $\mu\text{m}$ . The main components of the deposits are carbon (three chemical forms were observed by x-ray photoelectron spectroscopy) and silicon (two chemical forms: silicon dioxide and linear organosilicon). A silicon carbide presence is possible.

## I. Introduction

NUMEROUS investigations and results that were obtained during functioning of solar arrays on low Earth orbits (LEO) showed that, in many cases, the decrease of solar array power is caused by deterioration of the parameters of the optical system of the solar arrays (optical degradation). The optical system has multi-layered structure, consisting of outer layers (protecting glass plates) and inner layers (organosilicon lacquers and resins), antireflection coatings on the silicon plates of the solar array, and glass cloth layers. Optical degradation can be caused by several factors [1,2]: 1) contamination from the intrinsic outer atmosphere of the station, gas evolution from station volume, and products of incomplete combustion from plumes of station engines; 2) destruction of solar array materials by orbital atomic oxygen and solar UV radiation; 3) erosion of protecting glass-plate surfaces and their contamination by micrometeoroids and debris; 4) light-induced darkening of organosilicon adhesives; and 5) radiation-induced coloring of protective glass plates.

Now, it is known [3] that one of the main mechanisms of contamination deposit formation on optical and thermocontrol surfaces (besides condensation) is photochemical deposition. Solar radiation, mainly UV and vacuum UV components, induces numerous photochemical reactions with the participation of organic materials of spacecraft surfaces and organic components of the intrinsic outer atmosphere. Products of these reactions have enhanced attitude to contamination deposit formation on spacecraft surfaces. Besides, contaminations can be formed by destruction of organic materials in a solid state and by the diffusive transfer of formed products. So, the

study of contamination deposit on optical surfaces of solar arrays (of their chemical composition, morphologies, and other properties) has significant interest from the point of view of elucidating a mechanism of optical degradation for solar arrays and the development of methods to decrease optical degradation.

Other points of interests are connected with peculiarities of glass plates of solar arrays as substrates for contaminate deposition. First, during flight, one side of the fragment was predominantly illuminated by the sun while the opposite side was predominantly in shadow. So, comparative studies of sun-illuminated sides and back-sides give the opportunity to study the effects of solar illumination on contamination deposits. Second, the smoothness of the glass surfaces permits us, in principle, to obtain angle-resolved x-ray photoelectron spectra of contamination deposit layers. Here, results are given for the study of surfaces of solar arrays from the Mir space station, after prolonged functioning on LEO (for 10.5 years), and returning to Earth in 1998.

Mainly, three methods were used: 1) scanning electron microscopy (SEM) for the study of surface morphology, 2) local x-ray microanalysis (LXMA) for the study of the element composition of surface parts with dimensions  $1 \times 1 \mu\text{m}^2$  on the depths 0.5–1.0  $\mu\text{m}$  (the method is sensitive to carbon, oxygen, and other elements with atomic numbers above 11), and 3) x-ray photoelectron spectroscopy (XPS) or electron spectroscopy for chemical analysis (ESCA). The last method determines element composition (except hydrogen and helium) of surface parts with areas up to  $1 \text{ cm}^2$  on the depths of 3–5 nm. Different chemical forms of elements can be discovered on the basis of chemical shifts of spectral bands. Their contents can be determined in surface layers, with averaging on depths of 3–5 nm.

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These methods were used for investigation of other samples from the Mir space station in [4–6].

## II. Experimental

Front (sun illuminated) and back (shadow) sides of three fragments of solar arrays of the orbital space station Mir were studied. These sides belong to surfaces of two different protective glass plates on mutually opposite sides of a fragment. The reference sample, which had not been exposed in space, was also studied.

Figure 1 shows the solar array fragment in transverse section. It consists of two solar cells (1). They are connected electrically in a series by interconnector (7), which is soldered to copper buses (4, 5) with an Ag–Sn–Pb cover. Both sides of the solar cells are coated by glass cloth (6) impregnated by optically transparent silicone adhesive (silicone rubber, thermostable, low-molecular weight, phenylic) (9). There are protective glass plates (2, 3) on the front sides and backsides of each solar cell. Silicone adhesive is used to attach the cover glass to the solar cells (1) through the glass cloth (6). A solar array fragment is placed on the surface of the glass network substrate (8) of the solar array framework. It is attached by threads passing through the flank parts of the glass cloth on the backside (not shown on Fig. 1). During space station flight, protective glass plates on the front side were predominantly illuminated by the sun, while the protective glass plates on the backside were predominantly in

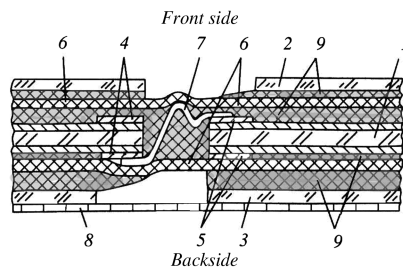


Fig. 1 Solar array fragment in transverse section.

shadow conditions (without direct illumination). Glass net (8) covers the backside of the protective glass plates, leaving free access of contamination from the intrinsic outer atmosphere.

Measurements by SEM and LXMA were made on the instrument Camebax MBX-1 (Cameca, France). Thin copper layers were deposited on sample surfaces for studying of their morphologies by SEM. This deposition was absent when the carbon content was measured by LXMA. Measurements by XPS were made on the instrument XSAM-800 (Kratos Analytical Instruments, U.K.). The excitation of spectra was made by characteristic x rays of Mg with photon energy of 1253.6 eV. Spectra were detected at the two values of angle  $\theta$  of the photoelectron takeoff: 90 and 35° (angle between

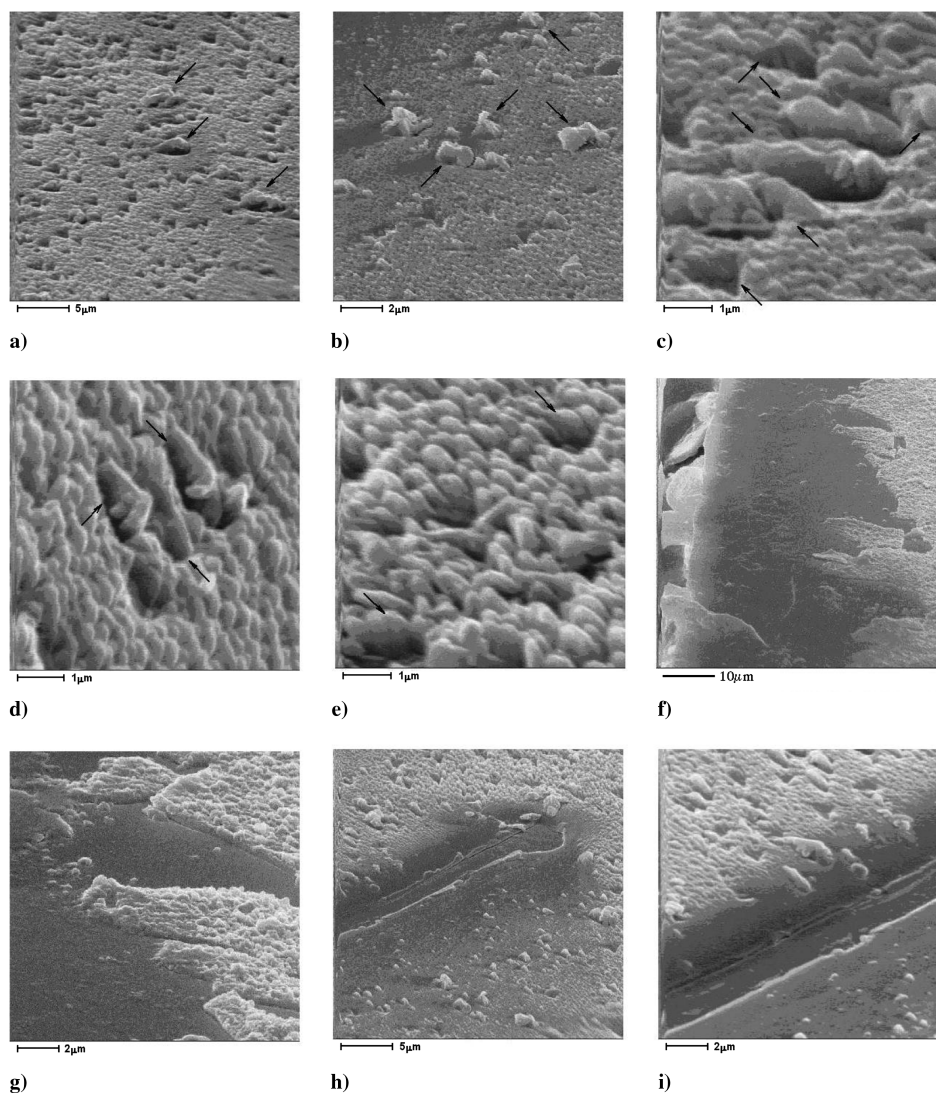


Fig. 2 SEM images of various surface parts on the front side of the solar array: a, b, c, d, and e) spheroid-shaped particles of deposits (irregularly shaped particles of debris marked by arrows); f and g) regions with partly removed contamination deposit layer; and h and i) trace of the micrometeoroid (or debris) impact.

direction of photoelectron exit and sample surface) correspond nominally (in ideal conditions) to probing depths of about 5 and 3 nm, respectively.

### III. Results

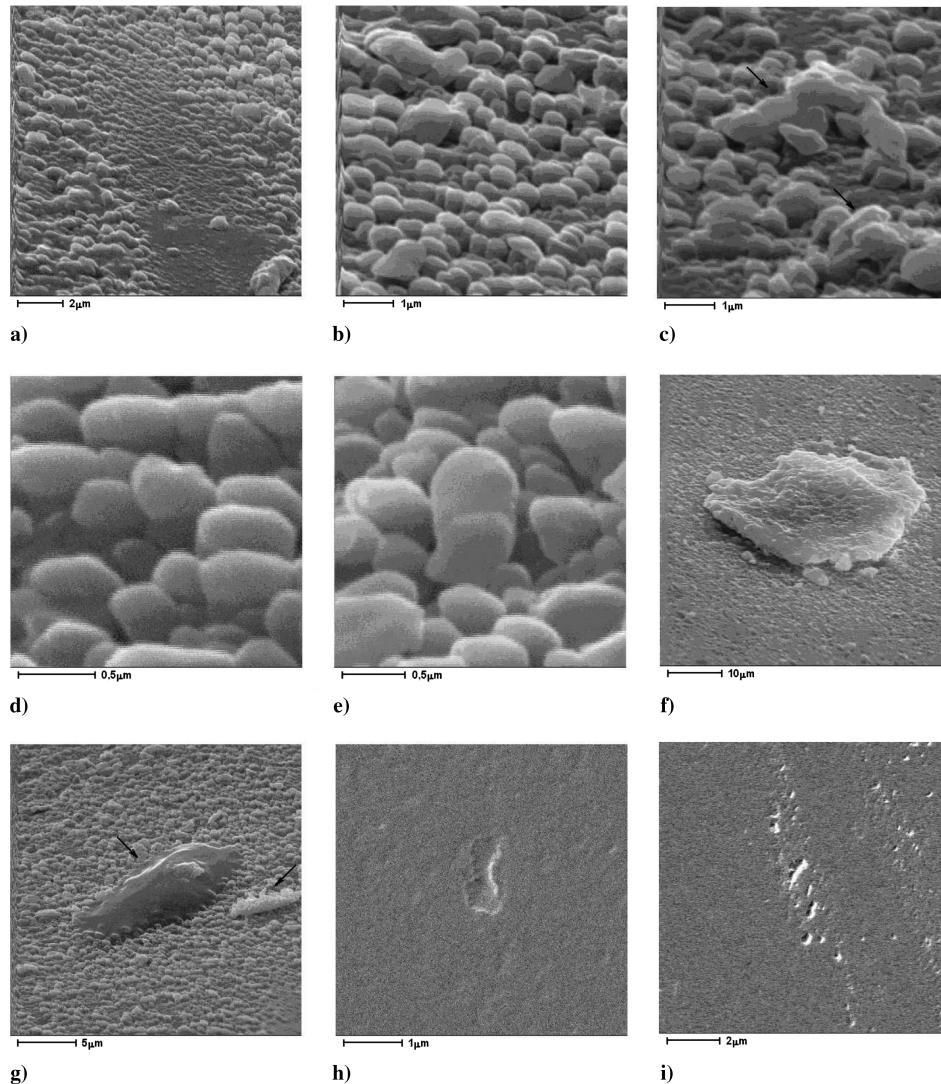
Figures 2–4 show morphologies of sample surfaces (reference sample and samples from the front sides and backsides of the solar array), which have been obtained by SEM in the regime of secondary electron registration at magnifications from 400 to 50,000. In comparison with the smooth surface of the reference sample, exposed samples of both types show the deposits consisted of particles of a spheroid shape with typical dimensions of 0.2–0.5  $\mu\text{m}$ . The front sides and backsides of the solar arrays have marked differences in morphologies. The particles of the front side have flattened shapes. On some areas, the particles of irregular shapes are observed with dimensions higher than 1  $\mu\text{m}$  imbedded into the contamination deposit. These particles appear to be debris particles. Their surface density is equal to about  $10^7 \text{ cm}^{-2}$ . The contamination deposit particles on the backside have more rounded shapes in comparison with the front side. They are packed less densely and have other alignments. Their long axes align mainly along the surface plane, while on the front side, they align predominantly at normal to the surface. The backside also contains flakes with dimensions of up to 15  $\mu\text{m}$  and thicknesses of about 1–2  $\mu\text{m}$ . They can be formed by scaled-up parts of the contamination deposit layer. Both sides

contain local surface damages with dimensions of 5–20  $\mu\text{m}$ . The authors believe this damage was caused by micrometeoroid impacts. The front side has surface regions not covered by contamination deposition. The backside of the solar array is completely coated by contamination. The authors believe the front surface exposure to atomic oxygen served to erode the regions of contamination.

LXMA data evidence the presence of carbon, silicon, sodium, calcium, chlorine, and phosphorus in the contamination deposit. The carbon content in the near-surface layer of the contamination deposit on the front side is not less than 10% by weight, while on the backside, it is not less than 25% (on the virgin glass sample, the carbon content is less than 0.5%).

Results of analysis by XPS are given in Table 1. For the virgin glass surface, there are significant differences in C1s spectra at photoelectron takeoff angles  $\theta = 90^\circ$  and  $35^\circ$ . The relative carbon content increases significantly when  $\theta$  changes from  $90^\circ$  (probing depth  $d = 5 \text{ nm}$ ) to  $35^\circ$  ( $d = 3 \text{ nm}$ ). This means that registered carbon is localized in the thin surface layer (thickness less than 5 nm). For exposed samples, the differences in carbon contents at various takeoff angles are only slightly visible. This can be explained by both the great thickness of the contamination deposit (much higher than probing depth) and its roughened surface, which can be seen on Figs. 2 and 3.

The photoelectron spectra of the virgin glass surface show the presence of carbon, oxygen, silicon, boron, sodium, and potassium. Spectral bands of O, Si, B, Na, and K are typical for boron–silicon



**Fig. 3** SEM images of various surface parts on the backside of the solar array. a, b, c, d, e, and g) spheroid particles belonging to deposits (irregularly shaped particles of debris are marked by arrows); f) one of the flake-shaped particles with dimensions near 15  $\mu\text{m}$  and thicknesses of about 1–2  $\mu\text{m}$  (such particles can be formed by chipping off parts of the contamination deposit layer); and h and i) reference samples.

glass K-208. Band C1s can be resolved on four Gaussian components that correspond to four chemical forms of carbon. Three of them can be related to surface contaminations from air (bond energies 285.0, 286.5, and 287.9 eV), but the form with bond energy 283.3 eV can be related with carbon in deeper layers (Figs. 4a and 4b).

The surfaces of the exposed samples contain carbon, oxygen, and silicon. Figures 4c–4f show C1s spectra of exposed samples at various photoelectron takeoff angles of 90 and 35°. The half width of the Si2p band is higher in comparison with the virgin glass. This band can be resolved on two Gaussian components corresponding to SiO<sub>2</sub> (103.7 eV) and to linear chains OSiO (102.5 eV), typical for organosilicon compounds (Fig. 5).

Decomposition of organosilicon compounds can, in principle, give not only silicon oxides SiO<sub>x</sub> but also silicon carbide. A search by XPS did not give positive results, but it is not possible to completely exclude its presence in the contamination deposit on the basis of the absence of the component with energy bond 100.4 eV in the Si2p signal (according to [7], SiC gives this component). Absence of this signal can be explained by its shift (because of electric charging

effects) to the region of 102.5 eV, where it is covered by the SiO<sub>x</sub> signal and cannot be resolved.

#### IV. Discussion

The main source of contamination, observed on the glass surfaces of the fragments of the solar arrays, is the intrinsic outer atmosphere of the space station. It originates from both the solar array and other station parts. Contamination sources from solar arrays can be their organic materials: organosilicon compounds (silicone and resin lacquers), hydrocarbons, and others.

The carbon content in the near-surface layer of contamination was higher for the backside in comparison with the front (sun illuminated) side. This result appears to be contrary to the expectation on the basis of the mechanism of photochemically enhanced contamination deposition from the intrinsic outer atmosphere. Because of this, we suppose that excessive carbon on the backside is supplied by hydrocarbons from the glass net supporting solar elements from the backside (the glass net is impregnated with paraffin oil). The other possible carbon source is organosilicon

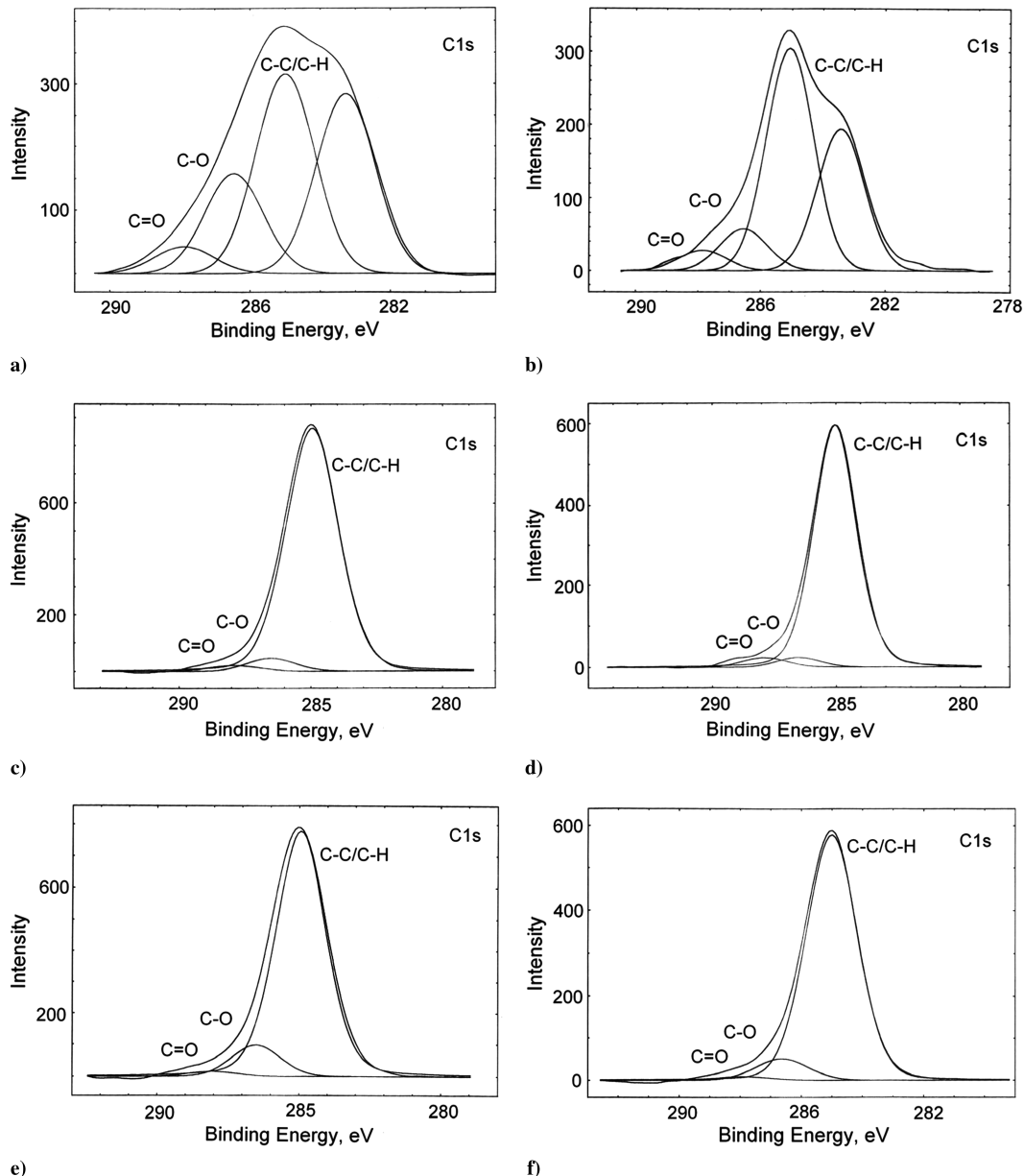


Fig. 4 Photoelectron C1s spectra of: a and b) reference sample, c and d) samples from the front side, and e and f) samples from the backside (a, c, and e display takeoff angles of  $\theta = 90^\circ$ , and b, d, and f display takeoff angles of  $\theta = 35^\circ$ ).



**Table 1** Results of analyses of samples by XPS

Element	Concentration, at. %	Binding energy, eV	Band intensity, %	Assignment
Virgin glass, $\theta = 90^\circ$				
Cl <sub>s</sub> (1)	25.7	283.3	37	C–C/C–H C–O C = O
Cl <sub>s</sub> (2)		285.0	39	
Cl <sub>s</sub> (3)		286.5	19	
Cl <sub>s</sub> (4)		287.9	5	
Ol <sub>s</sub>	45.0	532.8		
Na <sub>1s</sub>	2.8	1072.8		
K <sub>2p</sub>	2.0	293.8		
Si <sub>2p</sub>	20.3	103.2		
B <sub>1s</sub>	4.2	193.1		
Virgin glass, $\theta = 35^\circ$				
Cl <sub>s</sub> (1)	42.6	283.3	33	C–C/C–H C–O C = O
Cl <sub>s</sub> (2)		285.0	52	
Cl <sub>s</sub> (3)		286.5	10	
Cl <sub>s</sub> (4)		287.9	5	
Ol <sub>s</sub>	34.1	532.9		
Na <sub>1s</sub>	Trace			
K <sub>2p</sub>	1.1	293.6		
Si <sub>2p</sub>	17.7	103.2		
B <sub>1s</sub>	4.5	193.1		
Sample 1, front side, $\theta = 90^\circ$				
Cl <sub>s</sub> (1)	47.5	285.0	94	C–C/C–H C–O C = O
Cl <sub>s</sub> (2)		286.5	4	
Cl <sub>s</sub> (3)		288.0	2	
Ol <sub>s</sub>	30.0	532.9		
Si <sub>2p</sub> (1)	21.6	102.5	47	–O–Si–O– SiO <sub>2</sub>
Si <sub>2p</sub> (2)		103.7	53	
Fl <sub>s</sub>	0.9	689.7		
Sn <sub>3d</sub>	trace			
Sample 1, front side, $\theta = 35^\circ$				
Cl <sub>s</sub> (1)	47.2	285.0	93	C–C/C–H C–O C = O
Cl <sub>s</sub> (2)		286.5	4	
Cl <sub>s</sub> (3)		287.9	3	
Ol <sub>s</sub>	29.8	532.9		
Si <sub>2p</sub> (1)	22.1	102.5	40	–O–Si–O– SiO <sub>2</sub>
Si <sub>2p</sub> (2)		103.7	60	
Fl <sub>s</sub>	0.9	689.7		
Sn <sub>3d</sub>	trace			
Sample 2, front side, $\theta = 90^\circ$				
Cl <sub>1s</sub> (2)	47.7	285.0	89	C–C/C–H C–O C = O
Cl <sub>s</sub> (2)		286.5	8	
Cl <sub>s</sub> (3)		288.0	3	
Ol <sub>s</sub>	30.7	532.9		
Si <sub>2p</sub> (2)	21.6	102.5	44	–O–Si–O– SiO <sub>2</sub>
Si <sub>2p</sub> (1)		103.7	56	
Sample 2, front side, $\theta = 35^\circ$				
Cl <sub>s</sub> (1)	45.3	285.0	93	C–C/C–H C–O C = O
Cl <sub>s</sub> (2)		286.5	4	
Cl <sub>s</sub> (3)		288.0	3	
Ol <sub>s</sub>	32.9	532.9		
Si <sub>2p</sub> (1)	22.7	102.5	35	–O–Si–O– SiO <sub>2</sub>
Si <sub>2p</sub> (2)		103.7	65	
Backside, $\theta = 90^\circ$				
Cl <sub>s</sub> (1)	45.4	285.0	88	C–C/C–H C–O C = O
Cl <sub>s</sub> (2)		286.5	10	
Cl <sub>s</sub> (3)		288.0	2	
1s	32.9	532.9		
Si <sub>2p</sub> (1)	21.5	102.5	50	–O–Si–O– SiO <sub>2</sub>
Si <sub>2p</sub> (2)		103.7	50	
Sn <sub>3d</sub>	0.2	487.5		
Backside, $\theta = 35^\circ$				
Cl <sub>s</sub> (1)	44.3	285.0	91	C–C/C–H C–O C = O
Cl <sub>s</sub> (2)		286.5	8	
Cl <sub>s</sub> (3)		287.9	1	
Ol <sub>s</sub>	33.1	532.9		
Si <sub>2p</sub> (1)	22.4	102.5	45	–O–Si–O– SiO <sub>2</sub>
Si <sub>2p</sub> (2)		103.7	55	

compounds and their volatile components. These compounds are also the most likely source of silicon, which has been discovered in two forms: molecules with organosilicon chains SiOSiO and SiO<sub>2</sub> product of full oxidative degradation of organic parts of these molecules.

At the present time, the quantitative estimate of optical degradation of the solar array is a rather difficult task, because too many factors must be included in the calculations. Nevertheless, some approximate calculations give results in correlation with real data. For the solar array panel that was returned from the Mir space

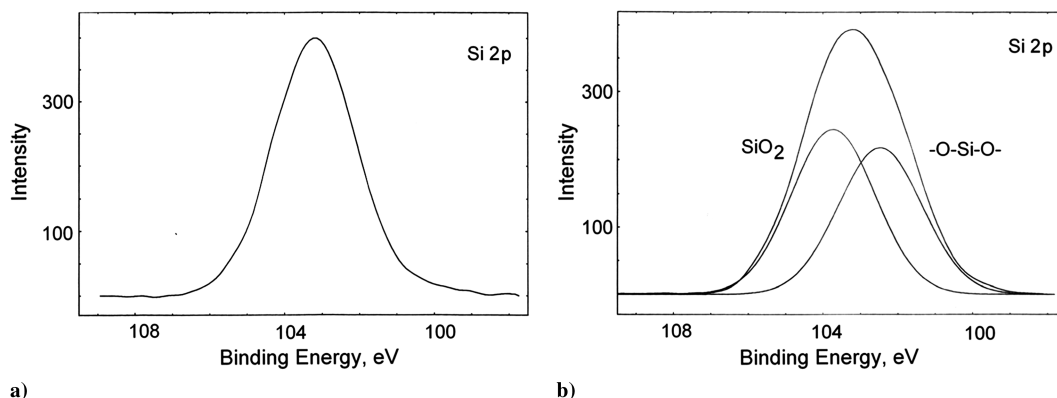


Fig. 5 Photoelectron Si2p spectra of virgin glass (left) and contamination deposit on the front side of the solar array (right).

station after 10.5 years of functioning in LEO conditions, optical losses were equal to about 8%. About 3% were caused by contamination of the optical system and about 3% (by erosion of protective glass plates by micrometeoroids and the remaining 2%) by some other factors, including radiation-induced coloring of protecting glass plates (1–2%) [1,2].

## V. Conclusions

Overwhelming parts of the surfaces on both the front and back-sides of solar arrays are covered by the contamination deposit with a thickness of up to 3  $\mu\text{m}$ . The surface of the contamination deposit has a granular structure. It consists of spheroid grains (from near spherical to extended, with dimensions of 0.3–0.5  $\mu\text{m}$ ). The structures of the contamination deposit (shapes and alignment of extended grains) are different on the front and backsides of the solar array. On some areas, debris and micrometeoroid particles of irregular shapes are observed with dimensions higher than 1  $\mu\text{m}$  imbedded into the contamination deposit.

LXMA data (element contents to depths up to 1  $\mu\text{m}$ ) showed that the contamination deposit contains Si, C, K, Ca, Cl, and P. The carbon content in the contamination deposit on the backside is at least two times higher in comparison with that on the front side. This result appears to be in contradiction with the expectation on the basis of the photochemical model of the contamination deposition from the intrinsic outer atmosphere of the space station. It can be explained by the presence of one additional path of carbonaceous contamination deposition for the backside, namely, from paraffin oil impregnation of the glass net.

XPS data for the solar array showed (probing depth up to 5 nm) that the contamination deposit surface consists of C, Si, and O as the main elements. Three carbon chemical structures and two silicon chemical structures were identified. The grain morphology of the contamination deposit surfaces gives them the roughness that impedes the obtaining of quantitative data on the depth dependence of the contamination deposit chemical composition by angle-resolved XPS.

Nitrogen was not found on the solar array surface (its content is smaller than 1%). This result suggests the absence of contamination by products of incomplete combustion from plumes of the space station engines (one of the rather common sources of contaminations).

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