ENHANCEMENT OF ATOMIC OXYGEN RESISTANCE OF CHARGE DISSIPATIVE ION BEAM TREATED POLYMERS

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ABSTRACT

Electric Orbit-Raising (EOR) launches to bring spacecraft to GEO are becoming more popular and yield some exposure of external materials to AO, due to the significant amount of time (months) the spacecraft remains at lower altitudes during the launch/transfer phases. The AO exposure remains much less than at a typical LEO mission, nevertheless, an additional requirement of LEO durability to a particular AO fluence is raised in this case for external materials. The worst-case AO fluence during EOR launch is estimated to be around 6E19 at/cm^2 or less. It is necessary, therefore, to develop external materials that can withstand all GEO orbit environment factors and, in addition, be resistant to the AO during such transit through the LEO environment.

A focused, multi-year effort was put to develop an ion beam surface treatment process of space polymers, named Carbosurf^{TM}, for surface charge dissipation. In a follow-up, an extended version of the treatment, called "Carbosurf+" (or simply "Carbo+" for short) was developed in which an additional stage was added at the end of the process that consisted of an ion beam deposition (IBD), forming a high-quality hydrogenated carbonaceous (DLC-like) thin film. Both "Carbosurf" and "Carbo+" have been used already in GEO for high frequency/high power space antenna applications. To impair to the developed surfaces new AO-resistant properties, further modifications of the Carbo+ treatment process were made with the results of this effort presented here.

In order to enhance the AO durability of the polymer surfaces, treated with Carbo+, an optimized Si doping during the top thin film deposition have been explored. The deposition conditions were adjusted by varying the Si doping levels and other parameters to ensure that the surfaces remain charge dissipative with a particular surface resistivity (SR) after production, and also after the maximum expected AO fluence. The treated polymers were tested in both a FAO beam facility and in oxygen plasma and SR was measured after exposure to various AO fluencies.

Complementary surface analyses, including SEM/EDS and, especially, low- and high-resolution XPS, allowed identifying the optimum Si doping level and the composition and structural surface transformations after production. The surface morphology, signs of erosion and surface transformations have been carefully analyzed after FAO beam or O-plasma exposures up to different AO fluencies. It was shown, that an optimal Si doping can drastically enhance the AO durability of the surfaces, covering as a minimum the needs for EOR launch. Also, based on the results of SR(T) measurements over a wide temperature range it was confirmed that the optimum Si-doping in the surface treatment did not compromise the low SR temperature dependence of the manufactured surfaces.

An alternative approach of non-doped thicker DLC films deposition, considering a part of the deposited film to be eroded in LEO as a "sacrificial" layer, have been also exploded and confirmed to be feasible.

1.0 INTRODUCTION

Electric Orbit-Raising (EOR) launches to bring spacecraft to GEO are being used increasingly as they require less fuel than conventional chemical rockets [1]. With electric propulsion, the thrust is weaker than with chemical rockets, but this small thrust can be provided for a long duration. Due to the significant amount of time (months) the spacecraft remains at lower altitudes before it reaches GEO, the external materials are therefore exposed to some AO (exposure to AO was previously negligible for a "fast" transfer to GEO with chemical rockets). The AO exposure remains much less than at a typical LEO mission, but is not negligible, with a typical estimated AO fluence around 6E19 at/cm^2 or less. Materials with very low thickness such as thin film coatings can therefore be impacted by this AO fluence.

Some of the space polymer materials that fit in this category are thin polymer films, surface treated by our developed and patented Carbosurf technology [2-4]. Carbosurf is a surface modification process that involves surface carbonization, based on ion beam treatment of the polymers [2-4]. This treatment enables the transformation of a very thin subsurface layer of the polymer into a highly carbonized structure, to get the desired surface resistivity (SR) in a static-dissipative range, while still being transparent to radio-frequency (RF) wavelengths. This material proved to be superior to alternate static dissipative coatings like Germanium on Kapton polymers (Ge/Kapton) in many aspects (robustness, resistance to humidity, possibility to get SR in a wide range, low T-dependence of SR over temperature SR (T), etc.), in particular when very high

RF power handling is required in modern space antennas. An improved version of Carbosurf was developed with the main objective to improve the durability of the material, in particular, the stability of the surface to handling, chemical and mechanical resistance, as well as stability over time in lab conditions (shelf life). This improved version was called Carbosurf+ ("Carbo+" for short) and the essence is of adding a very thin ion beam deposited (IBD) hydrogenated Diamond-Like Carbon (DLC) film on top, to meet all those requirements. the developed technology was scaled-up around 2012-2013 to the stage of flight materials manufacturing Next came the EOR launch requirements [1]. The erosion rate of DLC structures by atomic oxygen is known to be significantly less than for polymers, but for Carbo+ still both the DLC top layer and the carbonized surface underneath are very thin, and therefore there is some risk for them to be eroded by AO, even at the relatively low AO fluence resulting from EOR launch. Testing in two space simulation facilities confirmed the durability of charge dissipation and AO erosion resistance of the optimally Si-doped IBD hydrogenated DLC thin coatings.

2.0 EXPERIMENTAL
The results of an extensive multi-year R&D program have been used to develop innovative technological processes of ion beam surface treatment of organic polymeric materials and later – with high-quality ion beam thin coatings deposition on polymer space materials. It was followed by successful scale-ups and manufacturing of space flight materials. Ion beams treatment of organic polymers is considered to be very specific, since volatiles may be released from organic materials under ion bombardment, with significant elemental and structural changes mostly in the materials surfaces, up to organic-inorganic transitions. And it is important to mention, that Ion Beam Deposition (IBD) is a comparatively low rate method of high vacuum thin film deposition, but it is well-known to produce the highest quality films with excellent precision.

An industrial production high-vacuum facility with low energy high intensity technological ion beam source for ion beam (IB) treatment and versatile IBD and magnetron sputter deposition has been used for successful scale-up of the developed technology. We are currently able to do the production of large (up to 0.5mx1.75m) surface treated polymer sheets. Characterization of the material has been performed, including measurements of: Surface Resistivity (SR), variation of SR with temperature, thermo-optical characteristics, resistance to irradiation in GEO and MEO simulation facilities up to the levels of 15 years long space missions, RF properties (including PIM, RF losses and power handling), etc. For the structure and composition, a number of various complementary surface analysis techniques have been used, such as SEM/EDS, survey and high resolution XPS, etc. The results have been mostly described in Reports, in some publications, and in a granted US Patent [4].

Resistance to simulated GEO environment has been initially checked by testing the materials, treated by the developed technologies, at the Kompozit testing facility (Russia), described in [5]. Resistance to even higher MEO irradiation levels was checked afterwards in another facility.

The LEO simulation Fast Atomic Oxygen (FAO) beam facility in Japan described in [6] has been used in this collaboration for FAO testing experiments, and O-plasma exposure for severe AO testing in a manner, described in [6], has been performed in an oxygen (discharge) plasma for testing experiments of Carbo+ and Si-doped Carbo+ polymers.

The plasma exposure tests were conducted in a low-temperature, inductively coupled radio frequency plasma asher, similar to the one described in [5]. The asher operated at 13.56 MHz with the following settings: RF Power ~ 200 watts, oxygen pressure ~ 100 mTorr ± 5%, oxygen input ~ 100 sccm ± 5%, minimum average equivalent fluence ~ 1.9 x 10^{20} atoms/cm^2. The test and witness samples were placed in a holder and positioned in middle of the 8 L asher reactor. All samples were pre-conditioned in the plasma facility under vacuum for ~24-48 hours for outgassing. Mass change of the samples was measured with an electronic microbalance.

3.0 CARBOSURF AND CARBO+ TECHNOLOGIES FOR SPACE ANTENNAE APPLICATIONS
A number of materials, mostly commercially available polymer thin films, have been ion beam treated with the Carbosurf process and successfully tested. Materials that can be treated include, but are not limited to different hydrocarbon polymer films such as KaptonHN, Upilex and partially fluorinated polyimides [4]. All mentioned above polymer films have been successfully treated to provide their surfaces with charge dissipative properties.

A modernized, more robust, version of this surface treatment technology has been developed (Carbo+) and is used now commercially for space flights applications.

The main work has been later concentrated on research and manufacturing of Carbo+ treatment on one-side of Kapton100HN and Carbo+ treatment on both sides of Kapton500HN, mostly for modern space antenna applications.

These applications require not only long-lasting surface resistivity in a charge dissipative range, but also a number of other challenging requirements to be fulfilled, such as minimal impact on RF performance, etc. For instance, the treated Kapton100HN sheets have

been checked for RF losses and the excellent results of one of the tests are presented in Table I. These results demonstrate the fact of (absolute) absence of additional insertion and return loss in Kapton 100HN at high-frequency Ka band (26.5 – 36 GHz, as measured in WR28 waveguide) due to the performed Carbosurf surface treatment.

Table I: Surface Resistivity and RF Properties of Pristine and Carbosurf[TM] treated Kapton100HN [2]

Material	Treatment	SR (Ω/sq)		Frequency range 26.5-36 GHz	
		As treated	After GEO Rad. Testing	Insertion Loss (dB)	Return Loss (dB)
Kapton 100HN	Pristine	$> 10^{12}$	$\sim 10^{11}$	0.015-0.020	30-31
Kapton 100HN	Carbosurf	$13 \cdot 10^6$ to $25 \cdot 10^6$	$18 \cdot 10^6$	0.015	31

The temperature dependence of the SR, i.e. SR(T), is of particular interest for space application due to the well-known wide temperature range associated to antennas in space. Results of the measurements of SR(T) after the Carbosurf treatment of space polyimide films [3] are presented in Fig. 1 . A comparatively low T-dependence was found and confirmed in a wide SR values range, if to compare with the regular used Ge/Kapton, and this is highly beneficial for antenna applications in space [4].

The linear dependence $SR(T^{-1/4})$ means, following [7,8], that the variable range 3-dimensional hopping conductivity is the mechanism, that provides charge dissipation of our surface treated materials.
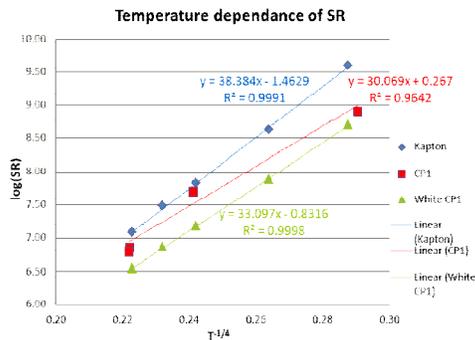

Fig.1. Semi-log graphs of the $T^{-1/4}$ temperature dependence of the surface resistivity of various materials with Carbosurf treatments [3].

Due to this comparatively low T-dependence, both Carbosurf and Carbo+ treated polymers will have higher SR and thus lower RF loss at very high temperatures and are less prone to a thermal runaway when subjected to very high RF power density (if to be compared to the commonly used Ge/Kapton).

The thermal runaway point (i.e. RF power density at which material will "burn" in vacuum) was estimated using Ku-band and Ka-band waveguides in TVAC at hot temperatures and gave the thermal runway points presented in Table II below.

Table II: Comparison of thermal runaway RF power density for various antenna sunshield materials [3]

Material (all samples of KaptonHN, 1 mil)	Approx. local RF power density at runaway (MW/m²)
Kapton100HN uncoated (not static dissipative)	More than 16.6 (no runaway reached at max. capacity of setup)
Carbo+ treated, SR of 1.5E8 ohms/sq (at Tamb)	14.2
Carbo+ treated, SR of 4E7 ohms/sq (at Tamb)	8.3
Typical Ge coated material	0.6 to 1.6 depending on samples

As can be seen, the RF power handling of the Carbo+ material is much higher compared to semi-conductor coatings like Ge/Kapton. We can also see that the power density required to initiate thermal runaway is higher for material having a higher SR, which was to be expected.

4.0 THIN IBD HYDROGENATED Si DOPED DLC COATINGS ON SURFACE CARBONIZED SPACE POLYMERS

Having experience in AO resistance enhancement and full protection of polymers by Si incorporation, using mid-energy Si ion implantation [9, 10], we decided to try using Si doping during the IBD DLC thin films deposition. Our goal was to reach a particular concentration of Si, to be enough for full protection of the surface structure under AO or FAO, but still to keep the surface charge dissipative. We finally found, adding silane at various deposition trials, that this goal can be reached, when the concentration of Si in the deposited Si-doped thin H-DLC coating reaches around 10-11 at% (by XPS). This conclusion is in a full agreement with recently published results of the studies about Si-doped DLC resistance to FAO [11, 12]. We used both O-plasma testing and, finally, FAO beam exposure in our studies.

Not only was it possible to achieve SR in the static dissipative range for Si-doped Carbo+, but it was confirmed that the SR(T) behavior was same as for

regular Carbo+, as can be seen in Fig. 2 for non-doped Carbo+ (on Kapton 500HN) and for two Si-doped Carbo+ samples (on Kapton100HN). The SR(T) variation of these samples can also be presented in similar way as Fig.1 to confirm the same hopping conduction mechanism – see Fig. 3.
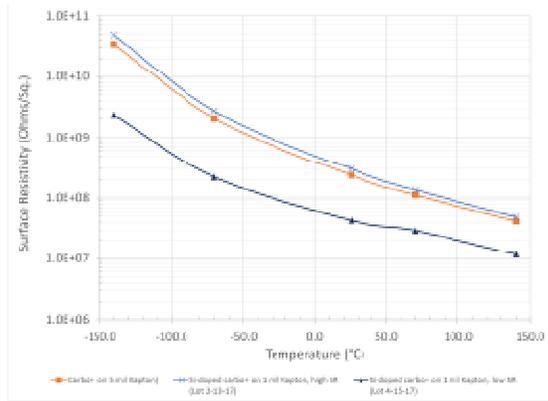

Fig.2. Temperature dependence of the surface resistivity of carbo+ on Kapton500HN and two Si optimally doped Carbo+ treated Kapton100HN samples with different SR at room temperature (RT)
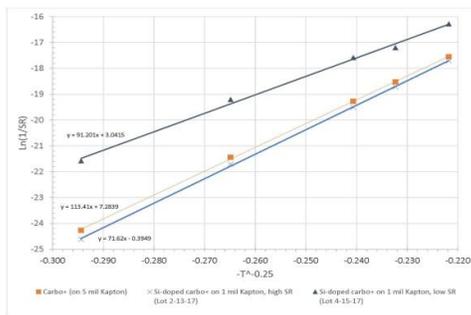

Fig. 3. Semi-log graphs of the $T^{-1/4}$ temperature dependence of the surface resistivity of Kapton500HN polyimide with Carbo+ treatment and two Si optimally doped Carbo+ treated Kapton100HN with different SR at room temperature SR (RT)

The results in Fig. 3 clearly show that it is also the same hopping conductivity mechanism in those Si optimally doped ion beam treated/deposited surfaces. Therefore, all the benefits, mentioned above for antennae application of those materials, can be easy forecasted. And, obviously, it is no reason for Si-doped Carbo+ to have different RF power handling, since variation of SR with temperature of Si-doped Carbo+ is the same as "regular" Carbo+.

5.0 LEO SIMULATION TESTING: O-PLASMA AND FAO BEAM EXPOSURE UP TO EXPECTED WORST-CASE DOSE IN EOR (6E19 at/cm2)

The confirmation of the protective ability of the best Si optimally doped IBD thin DLC films on Kapton100HN has been received by testing a number of samples, doped with Si to various concentrations, in O-plasma. At concentrations significantly lower than 10-11 at% (from XPS data), a reduction in the etching yield has been noticed as lower averaged mass loss in O-plasma, when compared to the non-doped "regular" samples.

However, the SR increased one-two orders of magnitude in these cases, depending on the original SR value and Si doping level, and for the 'worst case scenario' reached values close to those for an isolating material.

The surfaces of such samples after O-plasma testing looked matt, as with significantly increased roughness, and with a specifically developed surface morphology. In Figs 4-6 we can see that the optimally doped specimen did not change the surface morphology after O-plasma (Figs. 4 and 5), and the insufficiently doped sample #13 did show the post-testing developed surface morphology (Fig. 6)
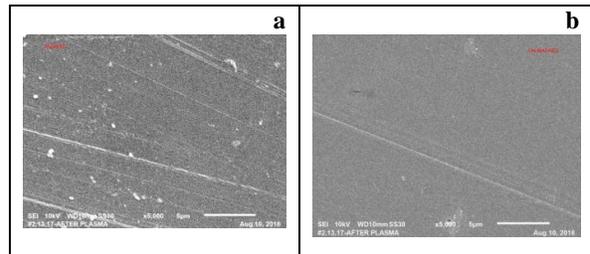

Fig. 4. Surface Morphology by SEM: sample of the optimally Si-doped sheet #2.13.17, exposed to O-plasma to effective AO fluence of 6E19 at/cm^2: a) Masked region; b) Exposed region
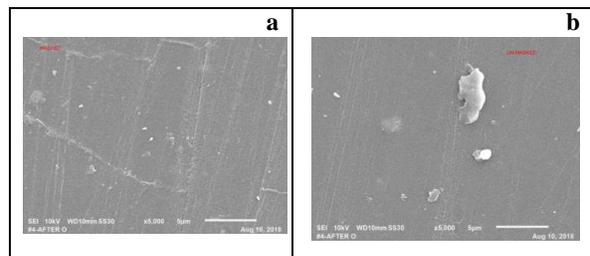

Fig. 5 Surface Morphology by SEM: Sample of the optimally Si-doped sheet #4.15.17, exposed to O-plasma to effective AO fluence of 6E19 at/cm^2: a) Masked region b) Exposed region

As can be seen from Figs. 4 and 5, there is practically no changes in surface morphology of these samples after AO plasma exposure up to effective AO fluence expected in EOR launches.
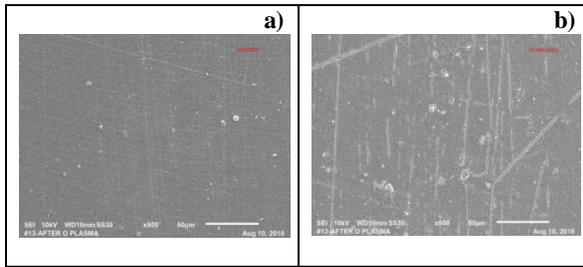

Fig. 6 Surface morphology by SEM: sample of a manufactured sheet #13 (with insufficient Si doping) after expose to O-plasma: a) Masked region; b) Exposed region.

For sample with insufficient Si doping, the film cracked in a number of areas and the surface of exposed region is relatively rough, with noticeable changes in morphology (Fig.6).

It is interesting to note that surface resistivity values and thermal optical characteristics are almost independent in our developed surface treatments. For instance, the two sheets of successfully doped materials, #2.13.17 and #4.15.17, had originally very close thermal optical characteristics, but differed by a factor 15 in SR values (~20 MOh/sq for #2.13.17 and ~300 MOh/sq for #4.15.17).

After exposure to O-plasma, the SR values have changed to ~52MOh/sq for #2.13.17 and to ~ 500MOh/sq for #4.15.17, that is functionally small change, and the alpha and epsilon values now differ from the original ones, but still are very close, as shown in Fig. 7.

Similar trends have been also found in samples tested in a FAO beam facility in Japan to four FAO fluencies: three of them being lower than EOR dose (2E18, 7.2E18 and 2E19 at/cm2) and the last one being equal to the AO fluence expected for EOR launch (6E19 at/cm2).

The measured SR after various levels of FAO exposure are shown in Fig. 8 for one optimally Si-doped Carbo+ sample (2b1) and for non-doped Carbo+ the average of results for several Carbo+ samples is shown.

As can be seen, the SR of non-doped Carbo+ increases with FAO exposure due to gradual erosion of the static dissipative layer. The charge dissipative properties of non-doped Carbo+ surfaces remain up to a dose between 7.2E18 and 2E19at/cm2. However, for Si-doped Carbo+ surfaces the charge dissipative properties last up to (at least) 6E19 at/cm2.
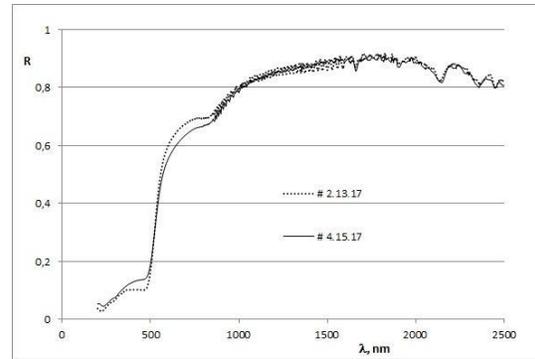

Fig.7. Apparent Solar Reflectance spectra over aluminum backing of two manufactured Kapton100HN sheet samples with Carbo+ treated surfaces - optimal Si doping and different SR(RT), both after O-plasma exposure up to 6E19 at/cm^2.
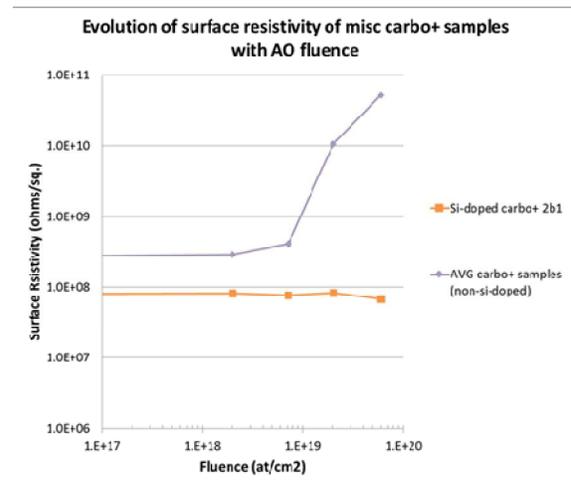

Fig. 8. Surface resistivity (SR) of non-doped and optimally Si-doped Carbo+ treated Kapton100HN after exposure to increasing AO fluence

For non-doped and the insufficiently doped specimens, the average mass loss has been different, depending on the Si doping level, and for the majority of them the SR changed significantly after the EOR-related FAO dose.

For the optimally doped clear and back metalized Kapton100HN samples, however, there was no mass loss after testing. The samples looked shiny and smooth, with SR variation of not more than a factor of 1.5 (that is a negligible change), remaining charge dissipative. A full confirmation of the AO protective ability of the best Si-doped IBD thin DLC films has been received: no mass lose and insignificant change of SR values as staying charge dissipative after the FAO exposure up to at least the expected dose seen during

EOR.

To understand better the mechanism of these phenomena, surface analysis using survey and high resolution XPS was conducted. The surface composition obtained from survey and high resolution XPS spectra are presented in Table III and in Fig. 9-11 for those two optimally Si doped samples before and after FAO testing.

Table III. Composition by XPS for the surfaces of optimally Si-doped Carbo+ treated Kapton100HN samples before (2b1 original) and after (2a1 and 2b1) FAO testing up to EOR-related FAO fluence

Samples ID/ Element Peak	Si2p	C1s	K2p	Ca2p	N1s	O1s
	Rel. At%	Rel. At%	Rel. At%	Rel. At%	Rel. At%	Rel. At%
2a1 - after FAO testing	17.95	38.94	0.12	0.22	1.01	41.76
2b1 - after FAO testing	11.01	55.41	0.06	0.66	1.58	31.29
2b1 original	8.97	67.99	0.03	0.19	0.96	21.87

As mentioned above, to understand better the chemical processes and reconstruction of the surface of Si-doped Carbo+ treated polymer before and after FAO exposure, high-resolution XPS was also conducted, and a part of the spectra, only for Si, are presented below in Fig.9-11
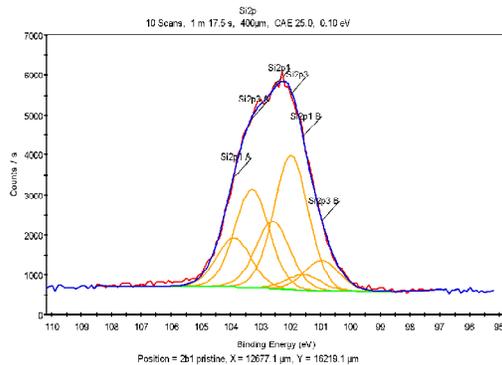

Fig. 9 Spectral deconvolution of Si2p bonding states for original sample 2b1. Only the Si2p$_{3/2}$ S-O components are labeled.

It can be seen from Table III, and later from Figs. 9-11, that, as a result of FAO exposure up to the AO fluence expected at EOR, both the changes of surface composition and re-distribution of the atoms among the chemical bonding states appeared at the FAO exposed surfaces. Carbon concentration of the exposed surfaces dropped significantly, the oxygen concentration increased, with more or less increase of the comparative Si concentration.

It is well-known, that the XPS method of analysis "feels" the surface composition in ~ 70-100A top surface layers of polymers, and in Kapton surface, due to polyimide composition, there is always ~ 6-7at% of N (by XPS). Therefore, from the data in Table III, for sample 2b1 original, as in our many similar results for other post-treated materials, it can be estimated, that the thickness of our deposited DLC thin films is ~100A, since N concentration in them is ~1at% - so, the Kapton underneath is not "seen" by XPS.

Since for the FAO exposed samples 2a1 and 2b1 we also do not see significantly more N in their post-exposure elemental composition, it means, that the thickness practically did not change for the best Si-doped films after FAO oxidative exposure at EOR-related LEO simulation testing! This is another, almost straightforward, indication of the full "self-protection" that the treated surfaces developed in this dangerously oxidative environment.

In Figs. 9-11 the spectral deconvolution of Si2p bonding states of the two Si-doped samples (a back metalized Kapton100HN and clear Kapton100HN), and then of the same surfaces after FAO exposer to EOR dose, are presented. The Si 2p spin-orbit (S-O) components (2p$_{3/2}$ and 2p$_{1/2}$) are clearly resolvable and are fitted with S-O separation of 0.61 eV and ratio of 2:1. Those samples are the following: 2b1(original) is the treated/deposited clear Kapton100HN, but not exposed to FAO (the treated/deposited 2a1(original) had almost the same composition, therefore not presented here). And the 2a1 and 2b1 are the samples exposed to FAO. The spectral deconvolution indicates the presence and significant redistribution of Si among same 3 main chemical bonding states: with Eb ~ 100.3 eV (SiC), with Eb ~102.4 - 102.6 eV (organic Si), and Eb`~ 103. 4eV (Si oxidized) in the surface layer The most important, that the high resolution data for Si2p$_{3/2}$ bonding states does show the drastic increase of the amount of Si in the oxidized states after FAO exposure, that is with the binding energy Eb=(103-103.5) eV. It looks like a significant amount of Si in IBD thin hydrogenated Si-doped DLC films experienced most probably, the oxidation to SiOx states, as in [13, 14] under FAO beam exposure and at LEO space MISSE experiments outside the International Space Station (ISS), covering the surface by this type of AO protective layers. And as we can see from the results, presents here, at the same time, with the surface retaining the charge dissipative properties at FAO exposure up to EOR-related fluencies.
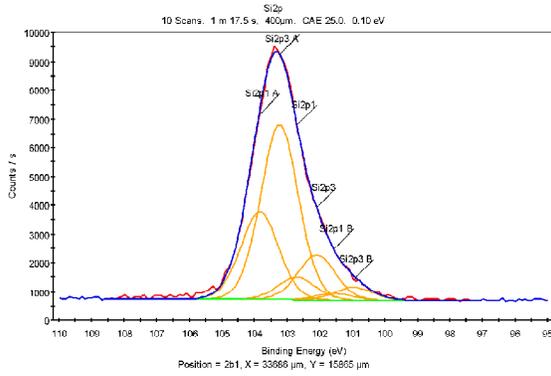
Fig. 10. Spectral deconvolution of Si2p3 bonding states for FAO exposed sample 2b1. Only the $Si2p_{3/2}$ S-O components are labeled.
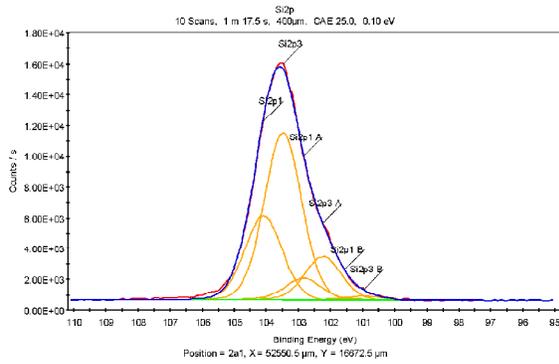

Fig.11 Spectral deconvolution of Si2p3 bonding states for FAO exposed sample 2a1. Only the $Si2p_{3/2}$ S-O components are labeled.

6.0 POSSIBLE ALTERNATE APPROACH TO WITHSTAND AO SEEN DURING EOR LAUNCH (THICKER DLC CARBO+)

Another option, that we also considered and are now working on, is the deposition of a thicker DLC layer, the "extra" part of which will be eroded away as a "sacrificial" layer while the spacecraft will be in and go through the LEO environment during EOR. This would allow to keep using in GEO the "regular" DLC layer of Carbo+ (not Si-doped), that is well analyzed, tested and successfully used already on some GEO spacecraft.

First experiments have been done with the DLC layer of a thickness $d_1=1.75d$, where d is the thickness of the "regular" DLC layer, used currently in production.

Samples of the sheets with DLC of thickness d_1 have been tested in O-plasma to the EOR effective AO dose of 6E19 at/cm^2, along with other coupons of the "regular" Carbo+, with DLC of thickness d, and of

Kapton100HN and Kapton500HN witness samples.

It was shown that for "regular" carbo+ (with DLC of thickness d), the charge dissipative layer was almost all eroded away, with just "leftover" indication of SR between $5x10^9$ - $7x10^9$ Ohm/sq. This is coherent with results of some our previous tests.

For the same test, the SR of the samples with thicker DLC increased less than a factor 2, going, for instant, from 72MOhm/sq to 110MOhm/sq. This change does not affect the material's functionality since the SR still stays in the charge dissipative range. However, in XPS survey, more N was seen than before testing, which is an indication that a lower thickness of DLC was left on the surface. Note that O-plasma test is considered more severe than the FAO beam testing, the last one better reproducing the LEO environmental conditions and influence on materials. Therefore, more work in deposition and FAO testing is now underway in order to find the optimal thickness and other features of those non-doped and the Si-doped thin DLC coatings. This presented and planned future work in this direction is to find the very best approach for production of the functionally and physically durable external polymeric space antennae materials, considering EOR launches, as well as for modern and future space antennae, to serve successfully in long-term GEO, MEO and interplanetary applications.

7.0 CONCLUSIONS

A number of highly beneficial functional surface properties have been incorporated in various space polymer materials by the so called Carbo+ technology. Carbo+ combines the ion beam treatment of those polymers with following ion beam deposition of thin Si-doped or non-doped DLC films. The beneficial properties include, but are not limited to: tunable SR values in a wide charge dissipative range, low T-dependence of SR over the space-related temperature range, no influence on the RF transmission at high frequencies, improved RF power handling compared to alternate charge-dissipative coatings (higher RF power to reach thermal runaway), etc.

A successful Si doping during the DLC film deposition has been achieved with confirmation of the resulting improved resistance to AO, up to full protection. Indeed, Si-doped Carbo+ materials did not show mass loss and had shown insignificant change of SR values after exposure to AO in O-plasma facility and at FAO beam exposure. It was therefore confirmed that Si-doped Carbo+ treated material can withstand at least the AO fluence seen during EOR launch (~6E19 at/cm^2), and still keep its main functional properties: being charge dissipative while serving later in the GEO environment.

Another option that is considered is to make thicker DLC Carbo+. A part of the thicker DLC layer would act as "sacrificial" layer that can be eroded away

during EOR, but to leave on the surface the "regular" thickness DLC layer, to provide functional charge dissipative properties of the surface to serve in GEO. Results so far indicate that this option would be viable. However, if the AO fluence is higher than the one seen during EOR (for example, in LEO missions), a solution with more AO protection such as Si-doped Carbo+ may be required.

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