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Transport of Sputtered Carbon During Ground-Based Life Testing of Ion Thrusters

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

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High voltage, high power electron bombardment ion thrusters needed for deep space missions will be required to be operated for long durations in space as well as during ground laboratory life testing. Carbon based ion optics are being considered for such thrusters. The sputter deposition of carbon and arc vaporized carbon flakes from long duration operation of ion thrusters can result in deposition on insulating surfaces, causing them to become conducting. Because the sticking coefficient is less than one, secondary deposition needs to be considered to assure that shorting of critical components does not occur. The sticking coefficient for sputtered carbon and arc vaporized carbon is measured as well as directional ejection distribution data for carbon that does not stick upon first impact.

Nomenclature

V_P	volume of carbon in primary deposition site
V_S	volume of carbon in secondary deposition site
S	sticking coefficient

I. Introduction

Electric propulsion devices such as electron bombardment (Kaufman) ion thrusters rely on high voltage insulators to prevent electrical shorting of components which are at significantly different potentials. Current ion optics being considered for high voltage ion thrusters use carbon based materials such as carbon-carbon composites or pyrolytic graphite. The long duration missions being considered which may utilize such ion thrusters will result in sputter erosion of the ion optics. Ground laboratory testing may employ carbon lined vacuum facilities to minimize back sputtered material onto the accelerator grid. Spalling of sputter deposited carbon may cause arcing where flakes pass between surfaces with large potential differences that are close together.[1,2] As a result, insulating surfaces such as ion optics insulators, thruster mounting insulators, wiring insulation and propellant isolators may receive sputter and arc vaporized carbon deposition which can potentially cause loss of performance of failure of thruster operation due to shorting (see fig. 1).[3]

Shadow shielding has been used effectively to prevent conductive deposits from shorting across insulator surfaces on most space and ground laboratory life tests of up to tens of thousands of hour's duration. The inspection of insulators, and isolators from the 30,352 hour extended life test of the NSTAR thruster showed faint but visible indication of sputter deposition on surfaces that indicated a sticking coefficient of less than one.[1] For missions now being considered, which use higher beam currents, higher voltages and of mission durations of 100,000 hours, one must be sure that carbon which does not stick upon first impact with a surface does not cause deposition which builds to a thickness that may cause an electrical short.

This paper reports on the investigation of the sticking coefficient for sputter deposited and arc vaporized carbon as well as the angular distribution of carbon being ejected from the primary deposition.

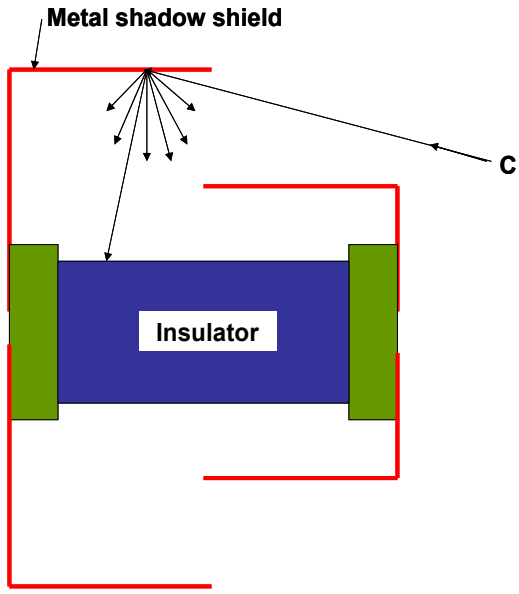

Figure 1.—Carbon deposition with less than unity sticking coefficient.

II. Apparatus and Procedure

Two different vacuum deposition systems were used to deposit carbon on a primary surface that contained fused silica witness samples which allowed measurement of the primary deposition thickness as a function of position as well as a silicon wafer that allowed measurement of the spatial distribution of secondary deposition (resulting from the carbon that did not stick to the primary deposition surface).

A. Sputter deposited carbon

The apparatus used to produce sputter deposited carbon consisted of a 3 cm diameter argon ion beam source which was operated at 1000 eV with the accelerator voltage at –150 V and an ion beam current of 50 mA for a duration of 2 hours to sputter carbon atoms off a carbon target located downstream of the ion source. Typical vacuum facility pressures during ion beam sputter deposition were ~1.3×10^{-3} Pa. Figure 2 shows a cross-section view of an argon ion beam sputtering system with the primary and secondary deposition surfaces indicated. Figure 3 is a photograph of a portion of the deposition chamber which mounts on the primary deposition surface and holds the secondary silicon wafer that was used to measure the angular distribution of carbon that did not stick to the primary deposition surface. The surfaces were housed within a box that allowed the sputtered or arc vaporized carbon to enter through a 2.54 cm diameter hole. The 5 cm diameter silicon wafer was mounted such that the downstream most surface contacted the carbon entrance orifice plate and the wafer was inclined at an angle of 46 degrees relative to the plane of the orifice plate. This allowed for the secondary deposition to accumulate over a wide range of angles with respect to the primary surface normal direction to allow measurements of flux as a function of ejection angle.

The silicon wafer was coated with a thin film of iridium (120 nm of Ir on a 20 nm Cr binder layer to the Si) to allow the thickness of the scattered carbon to be measured by variable angle spectroscopic ellipsometry (VASE) which was performed by the J.A. Woollam Co. Inc. This technique was selected to be used because of its ability to discriminate monolayer level thickness differences in thin coatings and the fact that the thickness of the secondary deposited film was less than 5 nm. To allow a comparison between coated and uncoated portions of the iridium coated silicon, an aluminum foil mask was placed over a portion of the wafer to prevent carbon deposition as can be seen on the right side of the wafer in figure 2. Measurement of the thickness of the primary carbon deposit was accomplished by allowing carbon to deposit on smooth fused silica wafers distributed across the primary deposition surface. Step heights between clean (tape covered) and deposited surfaces were measured using a Dektak 6M profilometer.

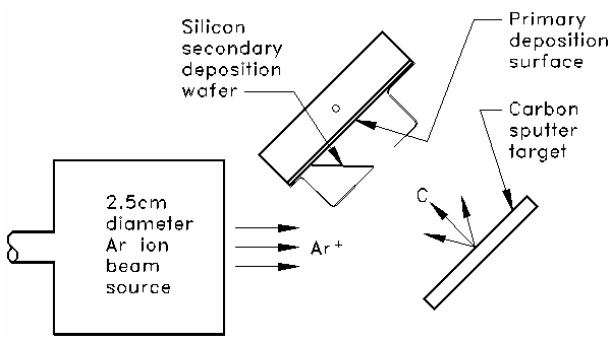

Figure 2.—Ion beam sputtering system.

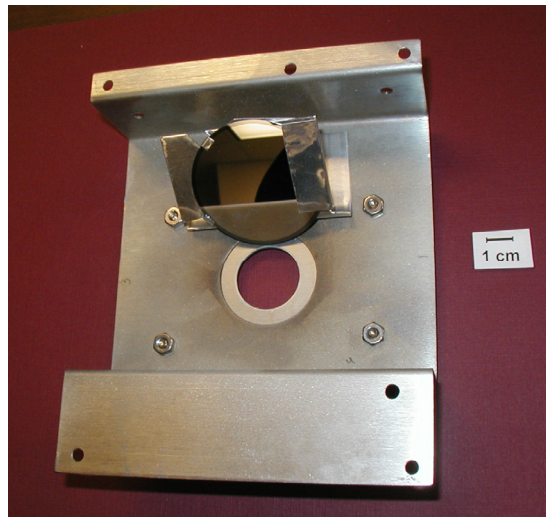

Figure 3.—Secondary deposition silicon wafer mounted on orifice plate.

B. Arc vaporized carbon

Carbon was also deposited by a vacuum arc between two closely spaced (0.25 mm apart) high purity (99 percent pure) carbon rods in a cryopumped vacuum of ~1.3×10^{-3} Pa. The arc was produced by a 15 kV, 60 mA, and 60 Hz power supply which powered the arc between two carbon surfaces for a total duration of 2.5 hours. The same orifice plate and Ir coated silicon wafer, as shown in figure 3, was used to document the primary and secondary deposited carbon for sputter deposition. However, for the arc deposited carbon, the thickness of deposition of both the primary and secondary deposition surfaces were much greater than for the sputter deposited carbon. This allowed acceptable accuracy for measurement of the thickness of deposits by conventional profilometry using a Dektak 6M profilometer to assess the thickness as a function of position for both the primary and secondary deposits. Figure 4 is a photograph of the carbon arc vaporization system. The thickness of the primary deposit was measured using fused silica witness slides that were partially covered by polyimide Kapton tape which allowed the step height of the deposit to be measured. Because the carbon electrodes had parallel flat faces, the deposit produced an elliptical pattern on the primary deposition surface. Thus, measurement of the spatial variation in thickness was necessary to compute the volume of the primary deposit. The primary deposition site was covered with optically flat fused silica slides arranged in a cross configuration to allow measurement of the thickness of the carbon deposit in two orthogonal directions.

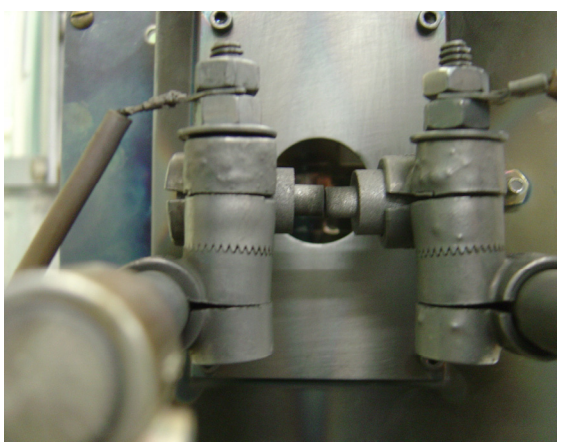

Figure 4.—Vacuum carbon arc deposition system.

The sticking coefficient, S, was computed for both the sputter and arc deposited carbon by computing the volume of the primary, V_P, and secondary, V_s, deposits, based on the thickness measurements made on the respective deposition surfaces. If one assumes that the volume of the deposition is negligible for the second and higher bounces, then the sticking coefficient is given by

$$S = V_P / (V_P + V_S) \tag{1}$$

III. Results and Discussion

A. Sputter deposited carbon

The thickness of the primary deposition was modeled based on a Gaussian fit to the thickness data measured by profilometry. The volume, V_P, of carbon deposited on the primary deposition surface was found to be 1.15×10^{-4} cm^3. The thickness of the carbon which did not stick to the primary surface but stuck to the secondary Ir coated Si surface was significantly thinner and not clearly visible to the unaided eye. Its thickness was measured using VASE. The spatial results of the thickness measurements are shown in figure 5. The protected region of the iridium-coated silicon wafer is indicated by a zero thickness portion of the wafer on the right side and the maximum deposit was less than 5 nm thick. The entrance aperture in the orfice plate for sputtered carbon was located approximately near the bottom of the graph.

By correcting the VASE carbon thickness data to correct for variations in radial distance and arrival angle from the center of the primary deposition site, a polar plot of the carbon angular ejection distribution was generated. Polynomial fitting the data to make sure that the polar plot crossed zero and 90° from the normal directions with zero slope resulted in the fitted curve drawn along with the data as shown in figure 6.

The ejection distribution is not a Lambertian (cosine) distribution which would appear as a circle on a polar plot. The ejection of carbon peaks at ~75° from the normal direction as opposed to in the normal direction which would occur for a Lambertian emission distribution. Integrating the polar distribution over the entire ejection hemisphere based on the fitted curve for the data produced a carbon volume, V_S, on the secondary deposition surface of 3.2×10^{-5} cm^3. Thus, the sticking coefficient for sputtered carbon is

$$S = V_P/(V_P + V_S) = (1.15 \times 10^{-4})/(1.15 \times 10^{-4} + 3.2 \times 10^{-5}) = 0.78 \quad (2)$$

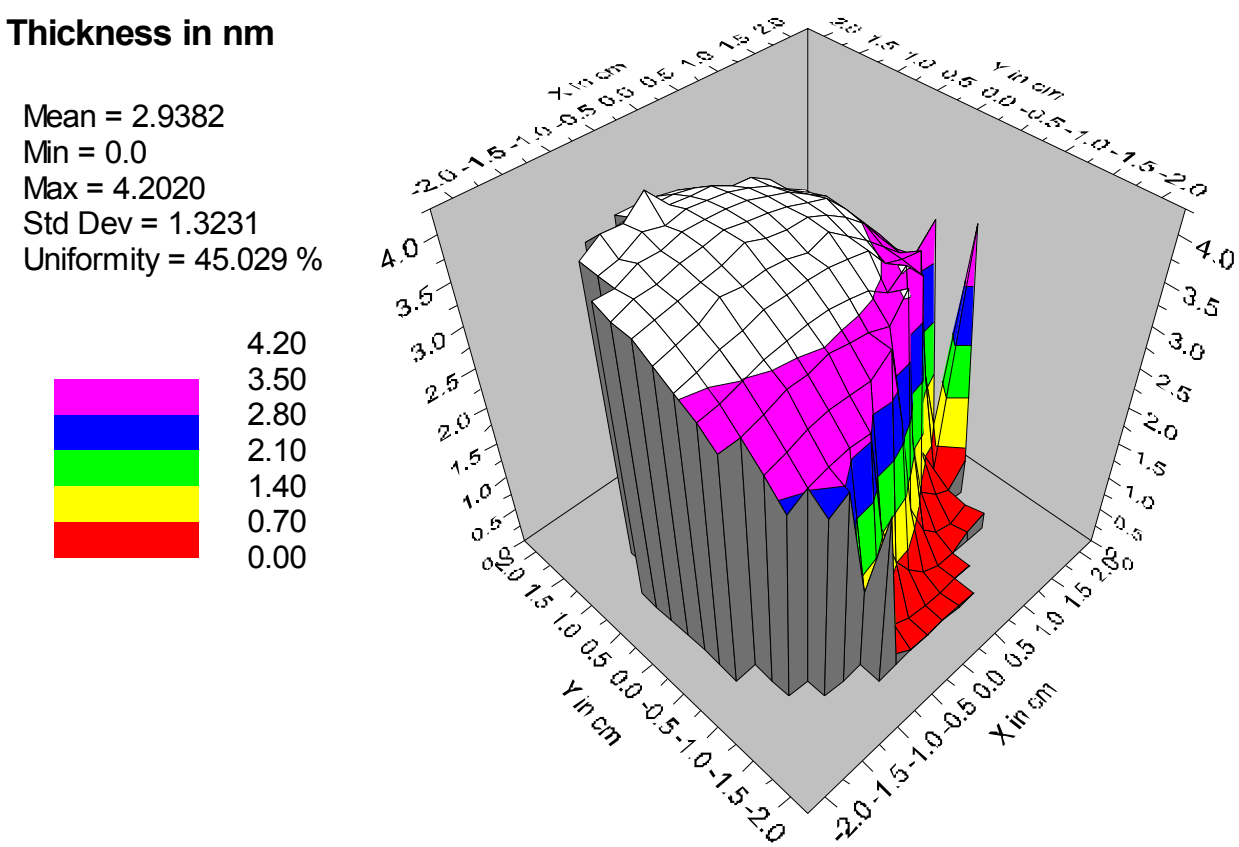

Figure 5.—Thickness, in nm, of carbon deposited on the Ir coated Si wafer during sputter deposition.

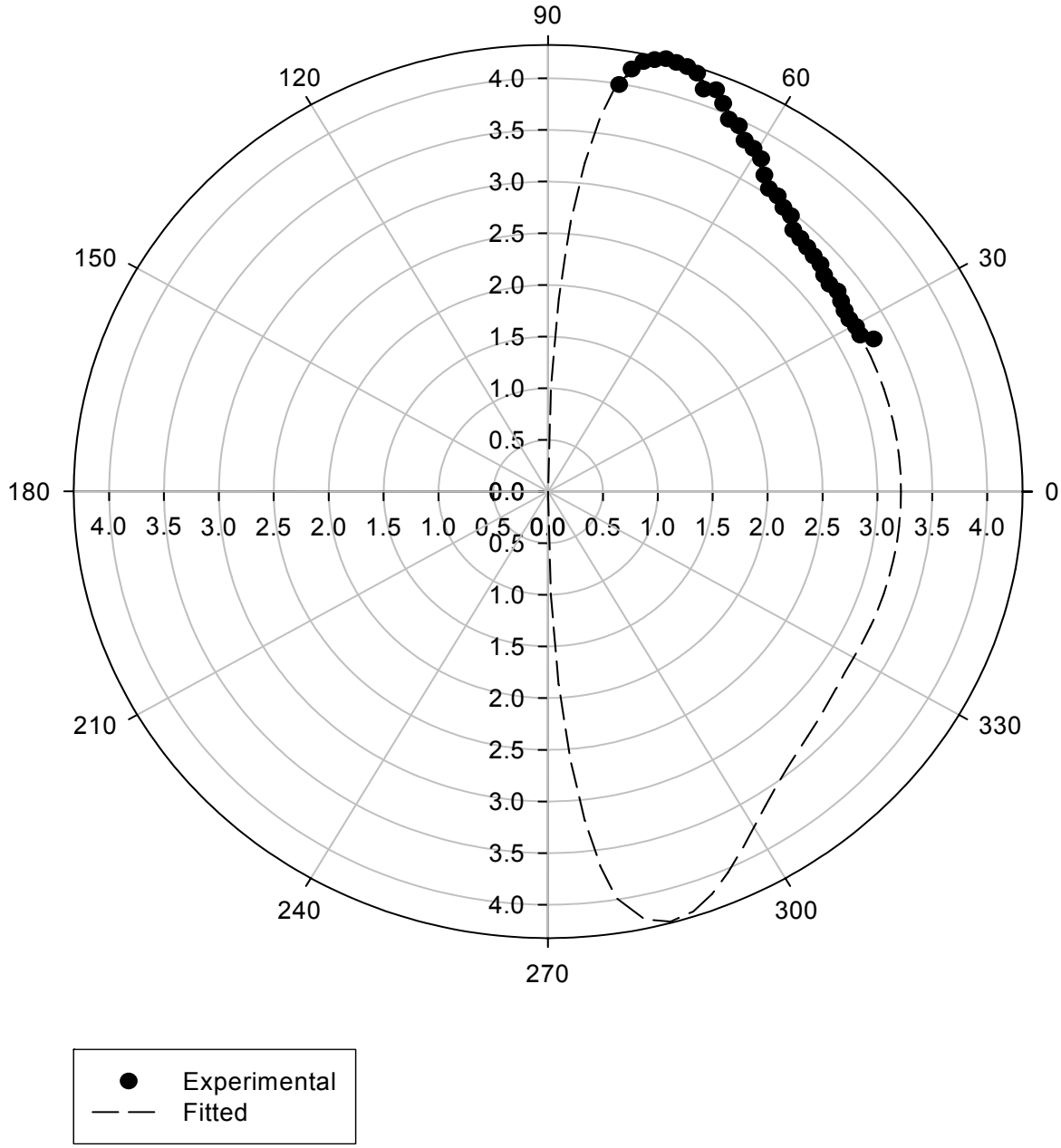

Figure 6.—Polar plot of carbon ejection angular distribution from sputter deposited carbon.

Thus, approximately 22 percent of sputtered carbon arriving at the primary deposition surface does not stick and deposits on secondary surfaces. As can be seen by the data point whose ejection angle is closest to the normal direction, there is a hint that at near normal angles the ejection flux may be higher than at 30°.

The implications of high ejection fluxes at angles close to the surface plane as well as near normal are that one must pay significant attention to shadow shielding geometries on insulators to assure conductive coatings do not build up during long duration exposures to sputtered carbon. Although sputtered carbon arrival at off normal incidence angles on the primary deposition surface may alter the angular ejection distribution results, the use of shadow shielding and wavy surface insulators appears attractive to prevent deposition on secondary surfaces that would result in unacceptable surface conductivity. Ground-based life testing facilities with carbon interior surfaces will produce back sputtered carbon onto vacuum facility surfaces in the vicinity of the ion thrusters which are primary deposition surfaces. These surfaces can then scatter a fraction of this flux onto thruster wiring insulation,

isolators and insulators if there is not adequate shielding present. The results from the 30,352 hour life test in a ground-based vacuum facility of the Deep Space 1 flight spare ion thruster showed strong indications of such scattering from primary deposition surfaces in that thruster components which did not have a direct line of sight to the downstream end of the vacuum facility had films of carbon deposited on them.[1]

B. Arc vaporized carbon

The thickness of the arc vaporized carbon which deposited on the primary surface was measured by profilometry and was found to be much thicker than for the sputter deposition carbon with thicknesses of up to 1,500 nm. The primary deposit was in the shape of a pyramid with an elliptical cross section. The primary volume of the deposit was estimated based on two independent profile modeling techniques. These computations produced a volume, V_P, of carbon deposited on the primary deposition surface ranging from 3.2×10^{-3} cm^3 to 5.0×10^{-3} cm^3.

The secondary deposition surface had a clearly visible deposit (see fig. 7) with a step height that was readily measured by profilometry. The entrance aperture for sputtered carbon was approximately located at the bottom of the wafer shown in figure 7. As can be qualitatively observed from this photo, the thickest deposit, which was 85 nm was located nearest to the entrance aperture. In spite of the rather smooth appearance to the coating, there were more variations in the thickness of the coating than for the sputter deposited coating. This may be due to the fact that microscopic particles of the carbon also were being ejected from the arc along with atomic carbon which could be seen as bright tracers.

After correcting for distance between the primary deposition site and locations on the secondary Ir coated Si surface as well as arrival angle relative to the wafer, a polar plot of the ejection distribution was produced and modeled using polynomial fits as shown in figure 8.

There is a preference for carbon ejection in the normal direction for arc deposited carbon. This may be a result of elastic scattering of the microscopic particles bouncing off the primary deposition surface. If the normal ejection peak is due to elastic scattered particles, then off normal incidence would probably result in a mirror image elastic scattering peak in the forward direction. It is interesting to note that the data point closest to the normal direction for the sputtered carbon in figure 6, which suggests the beginning of an increase in flux for ejection angles less than 28°, is similar to the angle for the onset of increased flux for the arc vaporized carbon of figure 8. These results are attractive in that conventional shadow shielding on ion thruster insulators and isolators would tend to cause the peak of the deposition flux to deposit on other than the ceramic insulating surfaces. Although there is significant uncertainty as to the magnitude of the normal ejection peak, the volume of the deposition associate with this peak is not as significant as appears on the figure 8 plot because the integration of the total volume of deposit is over a hemisphere where ejection at angles near 90 and 270° has much more impact than what happens at 0°. Integrating the polar distribution over the entire ejection hemisphere based on the fitted curve for the data produced a carbon volume, V_S, on the secondary deposition surface ranging from 4.5×10^{-4} cm^3 to 4.9×10^{-4} cm^3 depending upon whether one assumes the data modeling fit that produces 100 nm deposits for angles between –18 and +18 degrees or the intense lobe of up to 270 nm deposits at 0° as shown in figure 8.

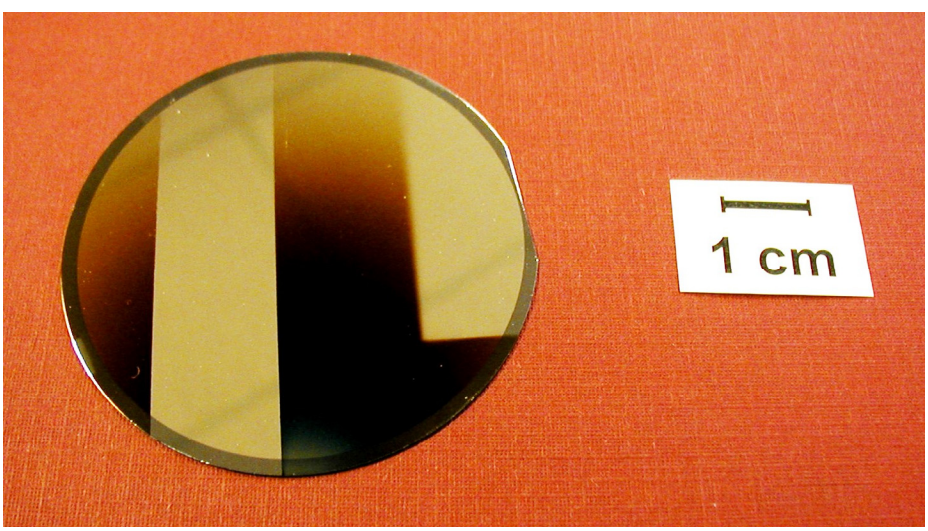

Figure 7.—Carbon deposited on secondary Ir coated Si wafer surface.

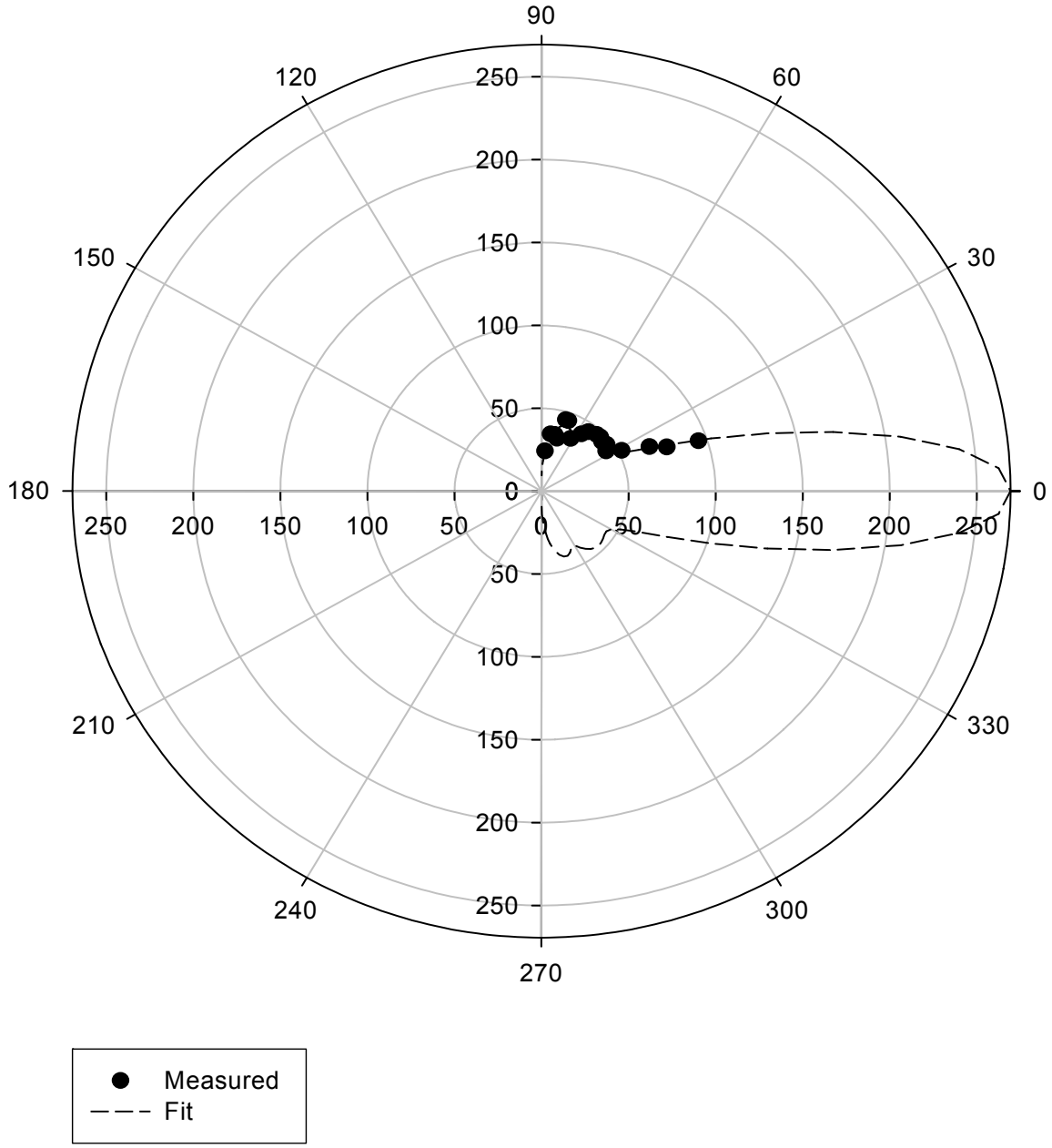

Figure 8.—Polar plot of carbon ejection angular distribution from arc deposited carbon.

Based on the range of primary deposition volumes predicted, and the range of volume of secondary deposits, and using similar calculations as for the sputtered carbon, sticking coefficients are predicted which range from 0.87 to 0.92 for arc deposited carbon.

IV. Conclusion

The sticking coefficient for sputtered carbon and arc vaporized carbon was measured as well as directional ejection distribution data for carbon that does not stick upon first impact. Surface profilometry or Variable Angle Spectroscopic Ellipsometry (VASE) was used to measure thin film deposits at the primary deposition site on fused silica slides or secondary deposition sites on Ir coated Si wafers. The sticking coefficient for carbon that was ion beam sputter deposited was found to be 0.78, whereas the sticking coefficient for arc vaporized carbon was found to be between 0.87 to 0.92. Angular carbon ejection distribution plots were produced for both sputtered and arc vaporized carbon. Results of the angular ejection distribution analysis and modeling indicate that for ejection of sputtered carbon, the dominant ejection is at approximately 15° from the plane of the primary deposition surface. For arc vaporized carbon, the highest rate of ejection is in the normal direction relative to the primary deposition surface. Because the sticking coefficients are between 8 and 22 percent less than unity, deposition on insulating surfaces that do not have a line of sight to the source of carbon may gradually become more conducting for ion thruster missions that are factors longer than have been tested to date. Such phenomena may be especially problematic for ground based life testing where significant amounts of carbon is back sputtered from carbon vacuum facility surfaces.

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[2]de Groh, K., Banks, B., and Karniotis, C., "NSTAR Extended Life Test Discharge Chamber Flake Analyses," paper presented at the 40th AIAA/AMSE/SAE/ASEE Joint Propulsion Conference and Exhibit, Paper No. AIAA–2004–3612, Fort Lauderdale, Florida, July 11–14, 2004.

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