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The Effects of Surface Modification on Spacecraft Charging Parameters

Amberly Evans and JR Dennison

***Abstract*—Charging of materials by incident radiation is affected by both environmental and physical conditions. Modifying a material's physical surface will change its reflection, transmission and absorption of the incident radiation which are integrally related to the accumulation of charge and energy deposition in the material. An optical analysis of the effect of surface modification on spacecraft charging parameters on prototypical Kapton HN and Cu samples is presented. Samples were roughened with abrasive compounds ranging from 0.5 to 10 µm in size, comparable to the range of incident wavelengths. They were also contaminated with thin layers of DC 704 diffusion pump oil. Using a UV/VIS/NIR light source and a diffraction grating spectrometer, measurements were performed on pristine and modified materials. The measured spectra confirmed that surface modification does induce changes in optical reflection, transmission, and absorption. The generally increased absorption observed results in increased photon energy deposited in the material, leading to increased charge emission through the photoelectric effect.**

***Index Terms*—About reflectivity, surface modification, spacecraft charging, photoyield**

I. Introduction

CHARGING of a material is affected by the physical conditions of the material [1,2], as well as environmental conditions [1,3]. Surface charging is typically limited to interaction of incident radiation in the outer 100 µm of a material. This limits the relevant incident energy of photons to $<10^3$ eV (IR/VIS/VUV), electrons to $<10^5$ eV and ions to $<10^7$ eV; these are the most intense spectral regions for typical space environments. Modifying a material's physical condition in this surface region will change its reflection, transmission, and absorption of the charge and energy of the incident radiation. Surface modifications include roughening and deposition of thin film contaminant or overlayers. This study considers surface modifications to materials in a laboratory setting that simulate the effects of the space environment on the materials.

Reflectivity, transmissivity, and thus absorptivity, are integrally related to the accumulation of charge and energy in a material. Increased absorption indicates increased photon energy being deposited in the material, which can lead to increased charge emission through the photoelectric effect. Increased surface roughness affects photon emission (optical reflection) or electron emission in various ways. Very shallow relief can increase emission by increasing the emitting area and by causing more grazing incidence. By contrast, deeper roughening [on the order of the secondary electron mean free path (~1 nm) or larger] can reduce electron emission and inhibit negative charging by reabsorbing emitted electrons. As an extreme example, a material comprised of very deep features with very thin walls acts essentially as a Faraday cup, effectively trapping all incident and emitted electrons and photons so that total electron yield approaches zero and only negative charging can occur. Contamination involves surface modification by depositing a foreign substance on the surface of the material. It is expected that as the thickness of the layer of foreign substance increases, the optical properties will be increasingly different from the uncontaminated material. Thus, modifying the surface of a material consequently affects the photon-induced charging of the material.

II. Theory

The photoelectric effect is one way in which spacecraft build up charge. Absorbed incident photons will deposit energy in the material, but photons that are reflected or transmitted do not deposit energy. It is possible, though, for reflected photons to be reabsorbed and then contribute to the total deposited energy in the material.

Upon contact with the material, light is reflected from the top surface or enters the material. That which enters either transmits all the way through, reflects off the bottom surface or is absorbed in the sample (Fig 1(a)).

From the Fresnel equations, reflectance, R, at normal incidence from a material of index of refraction n_1 into a material of index n_2 is:

$$R = \left[\frac{n_2 - n_1}{n_2 + n_1} \right]^2 \tag{1}$$

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When light is incident on a roughened material, things can change (Fig. 1(b)). The uneven surface scatters the reflected light diffusely, in all directions. The 'valleys' created by roughening, 'trap' some of the reflected light which can be reabsorbed by the material. The reflectivity due to diffuse reflectance, R_{diff}, is

$$R_{diff} = (1-\Delta)R \tag{2}$$

where Δ is the fraction of light reabsorbed. The absorption coefficient for the contaminant layer of thickness x in this scenario is

$$\alpha = -\ln(R)/2x \tag{3}$$

Contamination of a material by a thin layer creates a third reflecting surface for incident light, changing the overall reflection (Fig. 1(c)). Light can now also be absorbed within the contaminant layer. The reflectivity due to these multiple reflecting surfaces is:

$$R = \left[\frac{n_1-n_0}{n_1+n_0}\right]^2 + \left[\frac{n_2-n_1}{n_2+n_1}\right]^2 e^{-2\alpha_1 d_1} + \left[\frac{2\sqrt{n_1 n_2}}{n_2+n_1}\right]^2 \left[\frac{n_0-n_2}{n_0+n_2}\right]^2 e^{-2\alpha_1 d_1} e^{-2\alpha_2 d_2} \tag{4}$$

The first term on the right hand side of the equation represents reflected light from the first surface reflection, the second term reflection from the second surface with the absorption passing through the contaminant layer twice, and the third term reflection from the bottom surface with absorption passing through the both the contaminant layer and the substrate twice.

Reflected light from each layer can combine, leading to constructive or destructive interference at different wavelengths and causing thin film interference in the reflectance versus wavelength curves. Figure 1(d) illustrates this effect. From the thin film interference, the index of refraction can be calculated from two successive interference maxima of the wavelength spectrum as

$$n = \frac{1}{2d}\frac{\lambda_2 \cdot \lambda_1}{\lambda_2 - \lambda_1} \tag{5}$$

The total reflectance for a given incident wavelength is

$$R_{\text{int}} = \frac{1}{2}\left[\frac{n_1-n_0}{n_1+n_0}\right]^2 \cdot \begin{Bmatrix} (1+e^{-4\alpha d}) & ; & incoherent, \\ (1+e^{-2\alpha d})^2 & ; & coherent, constructive \\ (1-e^{-2\alpha d})^2 & ; & coherent, destructive \end{Bmatrix} \tag{6}$$

III. Experimental Methods

Two materials were analyzed, Kapton HN and copper. A pristine sample of each was used as a control standard. Four samples of 27 µm thick Kapton HN, a ubiquitous thin film insulating material, were prepared from as-received material. Five of OFHC Cu were prepared by polishing the surface, using decreasing sizes of polishing compounds, down to ¼ µm, so that the surface was mirror-like. Four roughened samples of Cu and two of Kapton were then roughened, each with a different uniform size of compound, creating different sizes of scratches in each sample (1, 3, 6 and 9.5 µm for Cu and 1 and 9.5 µm for Kapton). A fourth Kapton sample was prepared with a thin contaminant film. Dow Corning DC 704 diffusion pump oil (tetramethyltetra-phenyltrisiloxane)—with n=1.50—was used to mimic common spacecraft organic contaminants [4,5].

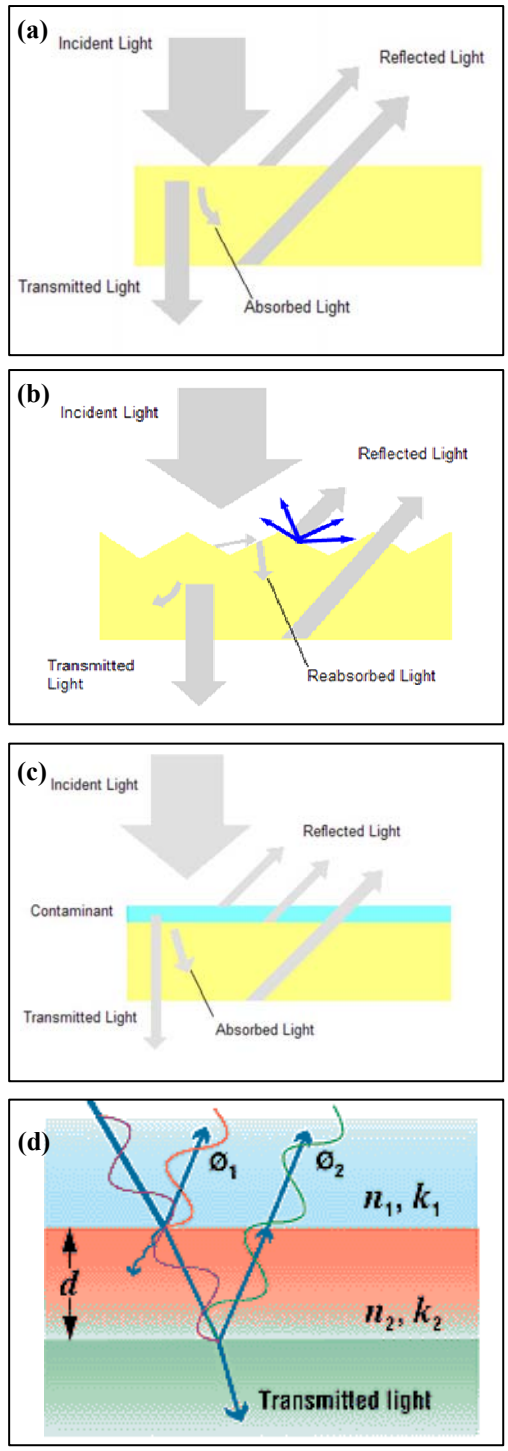

Figure 1. Scattering of incident light for (a) pristine material, (b) roughened material, (c) material with thin film contamination layer and (d) constructive and destructive interference from multiple layers.

Using a UV/VIS/NIR tungsten halogen light source (200 nm to 1100 nm) and diffraction grating spectrometer (Ocean Optics, Model HR 400), optical reflectivity measurements

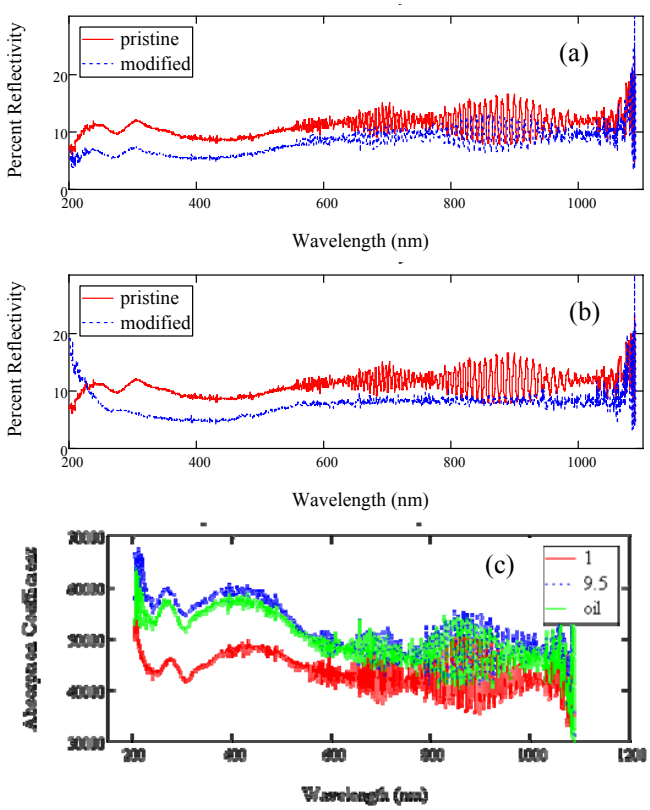

Figure 2. Specular reflectivity of 27 µm thin film Kapton HN samples . (a) Pristine sample (red) and sample roughened with 9.5 µm particles (blue). (b) Pristine sample (red) and a sample with a thin layer of DC 704 diffusion pump oil contaminant (blue). (c) Absorption coefficient as a function of wavelength for modified samples; (red) roughened with 1 µm particles; (blue) roughened with 9.5 µm particles and (green) contaminated with a thin layer of DC 704 diffusion pump oil.

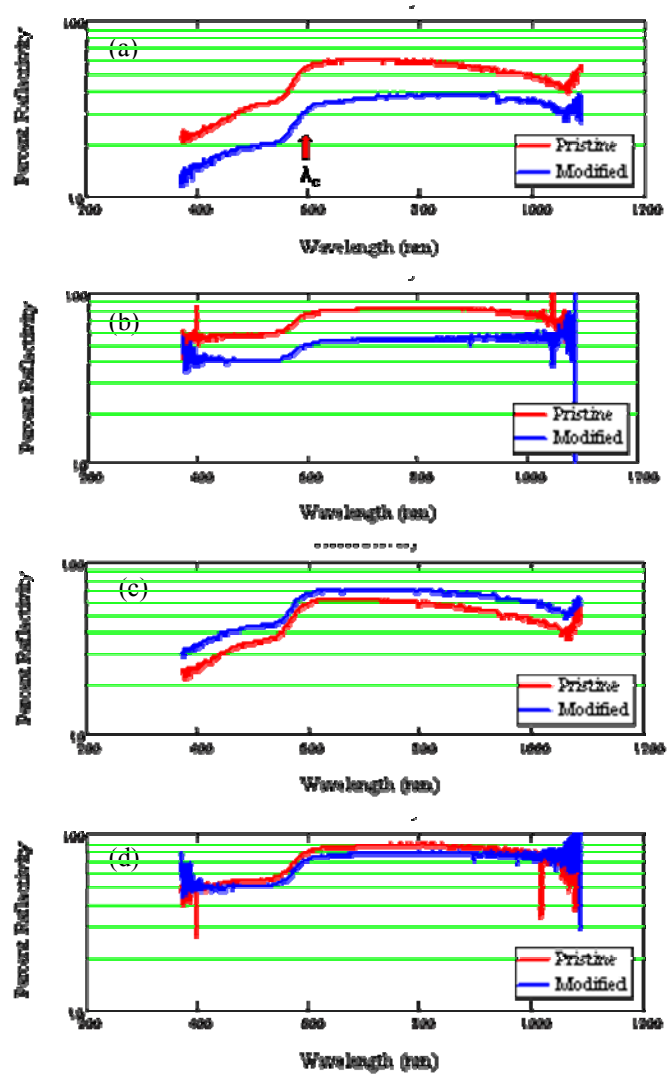

Figure 3. (a) Normal specular reflectance and (b) diffuse reflectance of Cu; pristine (red), roughened with 9.5 µm (blue). (c) Normal specular reflectance and (d) diffuse reflectance of Cu; pristine (red) and roughened with 1 µm (blue) abrasive particles.

were made. In this experiment, both normal specular and diffuse reflection were measured. Specular reflection was obtained using a fiber optic probe that was positioned perpendicularly to the sample. An integrating sphere was used to measure the diffuse reflection.

IV. Results

The results of Kapton HN reflectivity measurements are shown in Fig. 2. Figure 2(a) shows the difference between the pristine sample and that roughened with 9.5 µm. The average reflectivity is reduced to ~9.5% by roughening over the full range of wavelengths. Thin film interference oscillations are still observed even with roughening. These reflectance measurements were taken multiple times and the behavior of the spectrum is not consistent from one measurement to the next, suggesting that different areas of the roughened sample scatter differently; this is not surprising.

The average reflectance is reduced to ~8% by the DC-704 contamination (see Fig. 2(b)). This is consistent with a reduction based on Eq. (1) for n=1.35 for DC-704, in good agreement with the manufacturer's value [6]. Thin film interference oscillations are almost fully damped, suggesting a loss of coherence in the scattered light. At very low wavelength, the reflectivity of the contaminated sample increases. This effect is due to a property of the layer of oil.

For the Cu sample (Fig. 3), we observe a change in both normal specular and diffuse reflectance. When roughened with 9.5 µm particles, both normal specular (Fig.3(a)) and diffuse (Fig. 3(b)) reflectivity decreased. Indicated on the plots is the cutoff wavelength, λ_c, for Cu at 2.12 eV that results from 3d to 4s band transitions. In normal specular reflectance, the absolute change is 8-12% below λ_c and 12-30% above λ_c. Likewise, diffuse reflectance decreases 12-20% below λ_c and 20-30% above λ_c.

By contrast, roughening with 1 µm particles (Fig. 3(c)) actually increased normal specular reflectance 20-40% below λ_c and 15-20% above λ_c. This increase in reflectance is attributed to an increase in reflecting area due to the small scratches that are not deep enough to enhance reabsorption of light. Diffuse reflectance (Fig. 3(d)) decreases only 2-8% below λ_c and 5-10% above. λ_c

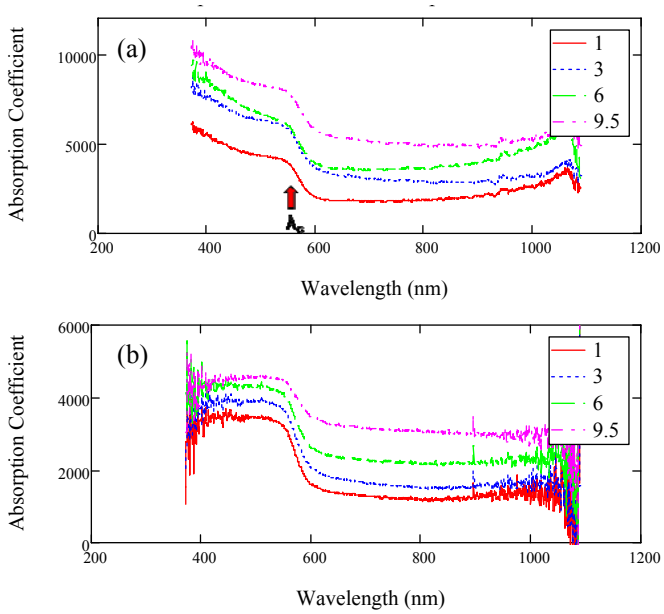

Figure 4. Absorption coefficient as a function of wavelength for samples of Cu roughened with 1 µm (red), 3 µm (blue), 6 µm (green) and 9 µm (magenta) abrasive compounds. (a) Normal specular reflectance. (b) Diffuse reflectance.

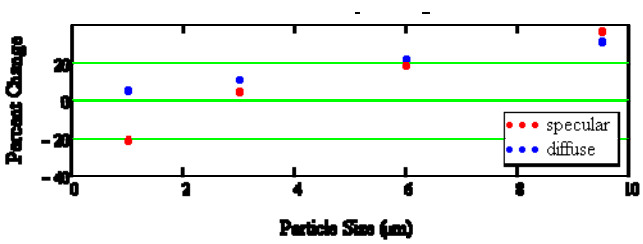

Figure 5. Average percent change, Δ, versus roughening particle size for normal specular (red) and diffuse (blue) reflectance.

V. Conclusion

The purpose of these measurements was to ultimately learn about the effect that these surface modifications have on charging. From the reflectivity, we can obtain absorptivity information. Absorptivity will finally lead to photoyield information.

The absorption coefficient for each modification of Kapton has been calculated using the above Eq. (3) and are plotted as a function of wavelength in Fig. 2(c). The absorption coefficient increases as roughening size increases and when a contaminant layer is deposited on the surface . This indicates that absorptivity increases upon roughening and—for DC 704 diffusion pump oil—upon contamination.

For the Cu samples, the absorption coefficient was calculated for both the normal specular and diffuse reflectance (Figs. 4(a) and 4(b), respectively). As roughening size increases, the absorption coefficient also increases. This is as expected. Increased absorption indicates that charging is increased through the photoelectric effect. Also calculated was the average percent change, Δ, in reflectivity, from Eq. (2). For both normal specular and diffuse reflectance, the

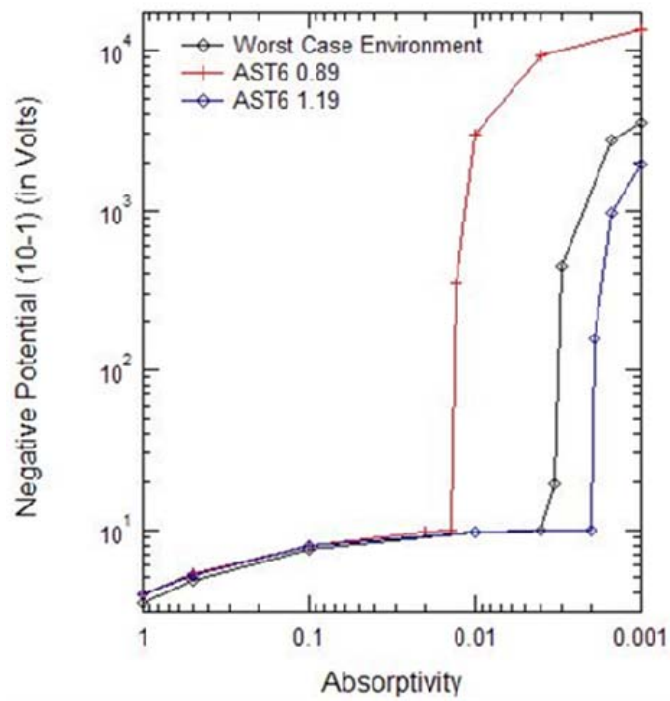

Figure 6. Equilibrium charging potential for a flat, two-dimensional satellite panel of Au as the fraction of absorbed photon energy decreases from 100% to 0%. Curves are for the 4 September, 1997 (squares), worst case (circles), and ATS-6 (triangles) geosynchronous environments [1].

relation between Δ and roughening particle size appears linear (Fig. 5).

For spacecraft charging applications, the effects of changes in reflectivity on photoyield have the most pronounced effects [1,7]. The effect of changes in absorptivity on photoyield, σ_{Ph}, and ultimately on spacecraft charging, have been considered. Based on arguments outlined by Lai [7] and Dennison [1].

$$\sigma_{Ph} = \frac{1}{N_e^{Tot}} \int \left[\dot{N}_{Ph}(E_{Ph}) \cos(\varphi) \right] \left[\frac{\sigma_{Ph}^{n}(E_{Ph})}{\cos(\varphi)} \right] \{[1 - R_n(E_{Ph}) - T_n(E_{Ph})] \cos(\varphi)\} dE_{Ph} \quad (7)$$

The first term in the integral is related to the decrease in cross sectional area with angle of incidence φ. The second term is the enhancement of the photoyield for normal incidence, $\sigma_{Ph}^{n}(E_{Ph})$, due to photon penetration depth. The last term in curly brackets is the optical absorptivity, $\mathcal{A}_n$, that corrects σ_{Ph} for the fact that only absorbed photons deposit energy in the material and can thereby produce photoelectrons. To a reasonable approximation, the absorptivity is equal to one minus the sum of the reflectivity plus transmission at normal incidence all scaled by the cos(φ) [1]. The inherent absorptivity and transmissivity at normal incidence are complex properties of the microscopic bandstructure and macroscopic dielectric properties of the material and depends heavily on the incident photon energy. These can be changed by structural changes in the material, or through UV or radiation damage. As discussed above, reflectivity at normal incidence depends more critically on surface modifications (on the order of incident optical wavelengths), through changes in surface roughness, contamination, surface degradation (e.g., from atomic oxygen), or temperature.

Under suitable circumstances, an increase in optical absorptivity can lead to threshold charging at finite values. Figure 6 shows the calculated equilibrium potential of a flat panel of Au for three specific conditions. In full sunlight these panels exhibit positive charging [1]. However, as the absorbtivity is reduce below from 2% to 0.2% (depending on specific conditions), the panel undergoes threshold charging. These results confirm the predictions of Lai, who calculated the critical temperature as a function of the reflectivity for several materials [7].

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