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“Feathered” fractal surfaces to minimize secondary electron emission

Charles Swanson and Igor D. Kaganovich

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I. ABSTRACT

Complex structures on a material surface can significantly reduce the total secondary electron emission from that surface. The reduction occurs due to the capture of low-energy, true secondary electrons emitted at one point of the structure and intersecting another. We performed Monte-Carlo calculations to demonstrate that fractal surfaces can reduce net secondary electron emission produced by the surface as compared to the flat surface. Specifically, we describe one surface, a “feathered” surface, which reduces the secondary electron emission yield more effectively than other previously considered configurations.

II. INTRODUCTION

Secondary electron emission (SEE) from dielectric and conductive surfaces can significantly change the flux and potential profiles at material interfaces, often limiting performance of many plasma applications and vacuum electronics such as RF amplifiers[1], particle accelerators, and Hall thrusters[2–4]. Various textures and treatments have been applied to material surfaces to minimize this secondary electron emission, such as triangular grooves[5–8], oxides[9], fibrous structures (velvet, fuzz, and foam[4,10–14]), and dendritic structures[15]. However, the search for practical solutions for surfaces which can extinguish secondary electron emission is still continuing, and we demonstrate that fractal, feathered surfaces are promising candidates.

III. GEOMETRIC CONSIDERATION

Consider a flat surface with some secondary electron emission yield (SEY, the ratio of secondary electron flux to primary electron flux) γ_{flat}. Now suppose there is some texture that can be applied to the surface to produce a reduced secondary electron emission yield, $\gamma = R\gamma_{flat}$, where $R < 1$.

Some examples of such textures are, as noted in Section II, triangular grooves[5–8], velvet and other fibers[4,10–14], and dendritic structures[15]. The mechanism for SEY suppression is the capture of first-generation secondary electrons emitted from deep inside the structure. In order to contribute to the net outgoing secondary electron emission flux, electrons must traverse this structure without intersecting any part of it and escape.

If this surface is continuous, we can consider a zoomed-in system of one surface element which appears flat. If this flat surface is textured again with smaller-scale versions of the surface, then an electron will have to traverse both the primary structure at the initial scale and the secondary structure at the smaller scale. Thus the reduction factor R can be reduced further by some $R_{new} = R \cdot R_1$.

This argument implies that if we continue this process N times and create an N^{th}-order geometry, which is a geometry that has had smaller versions of itself tiled onto its flat surface elements at N different smaller scales, it will be a suitable surface to greatly reduce the SEY from a flat surface.

Surfaces produced by this procedure will look self-similar at all scales. If the seed geometry is a triangular groove, for example, the recursed geometry is the Koch curve[16]. If $N \to \infty$, such a surface is a fractal.

It is not necessarily the case that $R_1 = R$. The numerical value of R is calculated by averaging over angular distribution of the emitted secondary electrons. For a flat surface this distribution is assumed to follow a cosine law[17]. However, this assumption does not hold for the fractal surface. The angular distribution of emitted secondary electrons from a complex surface can be strongly non-cosine at large distances from a small-scale structure due to geometrical consideration of the view angle as discussed in detail below. Therefore the SEY reduction for an N^{th} order recursion of geometry down to smaller scales does not necessarily scale as R^N.

IV. VELVET AS A CHOICE FOR THE SEED GEOMETRY

If the seed geometry is a velvet surface, which is a lattice of long whiskers grown onto a flat substrate, the recursed geometry will be a lattice of whiskers which themselves have whiskers grown onto their sides, like down-feathers, as shown in Figure 1. We refer to this surface as a “feathered” surface for this reason.

The reduction in SEY from a velvet surface was studied in our previous paper[13]. Velvet is most efficient at reducing SEY for electron flux normal to the surface, for $\theta \approx 0$, θ being the polar angle between normal to the surface and velocity of the incident primary electrons. The most efficient reduction is predicted for the velvet with rarely-spaced long whiskers. The necessary condition for maximum reduction in the SEY can be expressed as requirement for the dimensionless parameter

$$u \equiv \frac{2}{\pi} DA \gg 1, \qquad (1)$$

where A is the aspect ratio, $A = h/r >> 1$, h is the whisker height and r is the whisker radius, D is the whisker packing density, $D = \pi r^2/s^2 \to 0$, and s is the inter-whisker spacing,

When this condition is met, the reduction in SEY can be up to ten times for normal incidence $\theta \approx 0$.

However, velvet can not significantly reduce SEY for shallow incident angles. Reduction in SEY, R, for velvet is shown in Fig. 2 for the line labeled "Primary whiskers, $u = 2, 4, \infty$." The SEY reduction is minimum for a shallow incident primary angles $\theta \approx 90°$, where $R \simeq 0.5$.This results can be explained as follows: for $\theta \approx 90°$ the impinging primary electrons hit the whiskers near their tops, and secondary electrons are either emitted in the upward hemisphere or downward hemisphere with equal probability. Electrons emitted in the upward hemisphere escape, and in the downward hemisphere intersect velvet and do not escape. Hence $R \simeq 0.5$ for $\theta \approx 90°$.

Modification of a velvet surface to a feathered surface is needed to overcome this limitation in SEY reduction for shallow angles. Regarding processes that can yield feather-like structures, volumetric chemical processes have been identified which do cause velvet-like, fractal-like shapes to self-generate[18]. The same chemical processes that grow large-diameter velvet onto flat substrate may also be used to grow small-diameter velvet onto the sides of large-diameter velvet.

V. MONTE CARLO CALCULATIONS OF SECONDARY ELECTRON EMISSION YIELD

We performed a Monte Carlo calculation of the SEY of feathered surface. We used the same simulation tool that was previously used to simulate SEY of the velvet and was benchmarked against analytical calculations[13].

We simulated two surfaces: a velvet and a feathered surface that is velvet with one recursion, that is a velvet surface onto whose whisker sides many, smaller whiskers were placed. An example of the feathered geometry is depicted in Fig. 1. We found that the results were improved (R is smaller) if the secondary whiskers are placed at a 45° angle upward, rather than the straight-out normal to the whisker surface.

The velvet parameters that we used for this calculation were: the packing density $D = 0.04$, the aspect ratio $A = 80$, which correspond to a dimensionless parameter $u = \frac{2}{\pi} AD = 2$. For these parameters, a reduction of $0.2 < R < 0.5$ is expected for velvet. The small whiskers that were placed onto the sides of the big whiskers were 80x smaller. They have the same $D = 4\%$, with $A = 80 \cdot \sqrt{2}$, and were pointed upward at a 45° angle. Note that the radial extent of the secondary whiskers is therefore equal to the radius of the primary whiskers.

We numerically simulated the emission of secondary electrons by using the Monte Carlo method, initializing many particles and allowing them to follow ballistic, straight-line trajectories until they interact with the surface. The surface geometry was implemented as an isosurface, a specially designed function of space that gives correct feathered structure. The SEY of a particle interacting with a flat surface was assumed to follow the empirical model of Scholtz,[19]

$$\gamma\left(E_p, \theta\right) = \gamma_{max}(\theta) \times \exp\left[-\left(\frac{\ln[E_p/E_{max}(\theta)]}{\sqrt{2}\sigma}\right)^2\right]. \tag{2}$$

For parameters in the model $\gamma_{max}(\theta)$, E_p, $E_{max}(\theta)$, σ, we used those of graphite[13], assuming structures are carbon based. We initialized the primary electrons with an energy of 200eV. True secondary electrons, elastically scattered electrons, and inelastically scattered electrons were taken into consideration. At this energy, 2.3% of secondary electrons are elastically scattered according to our model. For more discussion on the model and its implementation in the Monte Carlo calculations, see our previous paper on SEE from velvet[13].

VI. SEY OF THE FEATHERED SURFACE AS COMPARED TO THE VELVET

The SEY function of primary angle of incidence θ and several values of parameter u are depicted in Fig. 2. The blue solid line, "Primary whiskers, $u = 2$," shows the SEY from the primary velvet described in Section V ($D = 4\%$, $A = 80$). The reduction in SEY for this case is between $R = 0.2$ for $\theta \approx 0$ and $R = 0.4$ for $\theta \approx 90°$. The green solid line, "Secondary whiskers, $u = 2$," shows the SEY from the feathered structure described in Section V (primary whiskers: $D = 4\%$, $A = 80$. Secondary whiskers $D = 4\%, A = 80 \cdot \sqrt{2}$, 80x smaller and pointed upward at a 45° angle). It is apparent that adding whiskers to the sides of the primary whiskers reduces the SEY dramatically for every θ. The dashed lines are the result of an analytic model described in our previous paper[13]. The first two dashed lines (red and cyan) correspond to $D = 4\%, A = 160$, $u = 4$ and $D = 4\%$, $A = \infty$, respectively.

The last, magenta line titled, "Side SEY half," shows the analytical result for SEY for the $D = 4\%$, $A = 160$ case, but with the SEY from the sides of the whiskers reduced by half. Our previous paper gives expressions for the contribution to the SEY from the tops and sides of the velvet whiskers and the bottom surface, $\gamma = \gamma_{tops} + \gamma_{sides} + \gamma_{bottom}$.The result, "Side SEY half," was obtained assuming the SEY from the sides of the primary velvet whisker is reduced by one half due to addition of the secondary whiskers, $\gamma_{sides} \to 1/2 \cdot \gamma_{sides}$.

The result for $u = 4$ is included to compare SEY for the feathered structure with the velvet with the larger radius because the addition of whiskers extending outward from the primary whiskers increases the effective radius, increasing the capture cross section and capturing electrons that may otherwise have escaped, see Fig. 1. From Figure 2, it is apparent that this effect is sufficient to explain the improvement in SEY of the feathered

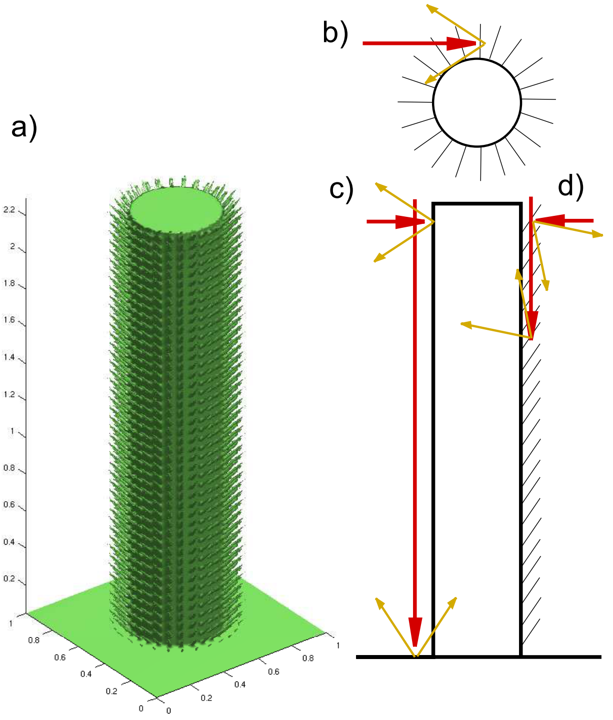

FIG. 1. a) Drawing of the "fiber on a fiber" geometry and schematic representations of the suppression mechanism. This geometry corresponds to a shorter, fatter ($D = 16\%, A = 10$ rather than $D = 4\%, A = 80$) geometry than the one calculated. At right are shown the effects described in Section VI: b) increase in effective capture area. c) Normal and shallow incident primary electrons on a velvet geometry. d) Normal and shallow incident primary electrons on a feathered geometry. Red arrows correspond to primary electron trajectories. Yellow arrows correspond to example secondary electron trajectories.

geometry at normal incidence, $\theta \approx 0$, because red dashed line coincides with the green line.

Simply increasing the radius of the primary whisker by this amount would increase D to 16% (and decrease A to 40, and increase u to 4). This increases the number of electrons that are emitted from the tops and escape. Figure 1d shows that this larger D effect is not the case when the effective extra radius is made up of secondary whiskers; instead, the secondary electrons are directed inward and are captured by the structure.

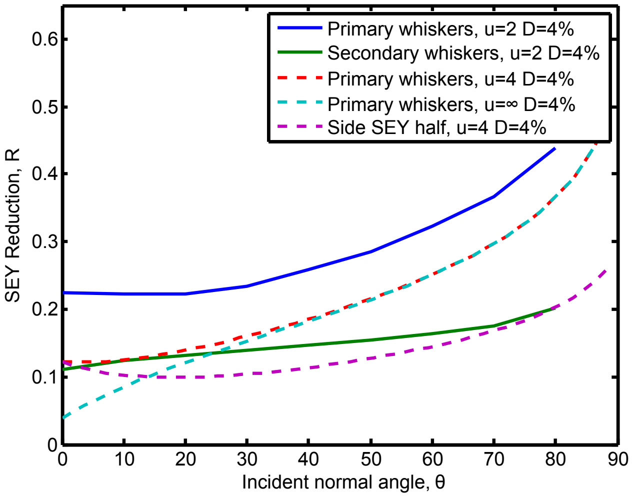

FIG. 2. Solid lines show the result of the numerical Monte Carlo calculation: reduction in SEY of the considered $u = 2$ graphite velvet either without another recursive velvet grown onto the whisker sides ("Primary whiskers, $u = 2$"), or with this smaller velvet ("Secondary whiskers, $u = 2$"). Also shown (2 dashed lines) are the result of the analytic model in our previous paper[13] for the case of velvet with $u = 4$ and $u = \infty$ for velvets with $D = 4\%$. Also shown (last dashed line) is the result of the analytic model for $u = 4, D = 4\%$, but with the emission from the sides of the whisker reduced by half.

The result for $u = 4$ with the SEY from the sides of the whisker reduced by half is included to explain the other interesting observation for shallow incidence angles ($\theta \approx 90°$) that shows SEY reduction in the feathered case. Indeed, the feathered geometry even out-performs an infinitely long velvet case, that of $u = \infty$ in this regime. This is because, as depicted in Figure 1c, when primary incidence angle is shallow, primary electrons hit velvet whiskers very close to their tops, and nearly half of the secondary electrons are emitted with velocity in the upward direction and escape. As depicted in Figure 1d, primary electrons incident with shallow angles hit feathered whiskers very close to their tops, but SEE is suppressed by the secondary whiskers. The local angle of incidence on secondary whiskers ranges from 45° to 90° dependent on impact parameter to the primary whisker relative the center of the primary whisker, so we have conservatively assumed that the SEY from the sides is reduced by the worst factor expected for the secondary velvet, one half, $\gamma = \gamma_{tops} + \gamma_{sides}/2 + \gamma_{bottom}$.

These results indicate that the SEY from a surface can be suppressed by adding a feathered structure to the surface. Furthermore, we speculate that these results can be generalized to other fractal-like shapes, which consist of surfaces that have been scaled down and tiled onto themselves.

VII. CONCLUSIONS

We simulated and verified that the feathered structures can suppress SEY better than a velvet surface. A velvet surface with one recursion of smaller velvet whiskers grown onto the primary whisker sites looks like a down-feather, and so we refer to such surfaces as "feathered." Such feathered surfaces are suitable for suppressing secondary electrons even for shallow incident angle of primary electrons. Total reduction in SEY in the range $R \approx 0.1$ for $\theta \approx 0$ and $R \approx 0.2$ for $\theta \approx 90°$ can be achieved for feathered structure.

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