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Cite as: AIP Advances 9, 125009 (2019); https://doi.org/10.1063/1.5120519
Submitted: 18 July 2019 . Accepted: 18 November 2019 . Published Online: 04 December 2019

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Ion-induced electron emission reduction via complex surface trapping

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ABSTRACT
A Monte Carlo model is developed and validated to understand the ion-induced electron emission (IIEE) characteristics of complex surfaces and to show the importance of using precise geometric features to examine surface morphology effects on the yield. The decrease in IIEE from carbon velvet is accurately simulated with two distinct geometries (based on SEM images), one composed of slanted, sparsely distributed fibers and the other of tightly packed, vertical fibers. Simulation results for tungsten fuzz using a cage-like geometry predict a reduction in the yield of ~50% compared to flat W, contradictory to previous estimates. Collisional heatmaps using the cage geometry show that the angular independence of IIEE is due to electron trapping by the horizontally oriented fibers. These insights into the emission behavior of these surfaces provide guidance for the design of new surfaces that can improve the performance of plasma devices.

The emission of electrons from bounding surfaces due to bombardment of ions and primary electrons can significantly affect the plasma sheath and, in turn, the interactions between the plasma and the surface. Because emitted electrons enter the plasma at low energies, they decrease the sheath potential, causing high electron energy loss through the sheath from the plasma. From the material’s perspective, this increases wall heating while reducing the ion incidence energy. Hence, the sputtering, secondary electron emission (SEE), and ion-induced electron emission (IIEE) yields are affected. This in turn can impact the performance of a wide range of plasma devices, from electric propulsion devices to tokamaks.

To suppress the effects that electron emission and sputtering have on the plasma, featured surfaces have been shown to trap emitted electrons and sputterants, decreasing the yield. In particular, carbon velvet and tungsten fuzz have been shown to reduce electron emission as compared to flat surfaces of the same material, which can improve the performance of miniature Hall thrusters (on which magnetic shielding is challenging) and fusion devices. However, experimental and modeling work has focused on secondary electron emission and largely neglected ion-induced electron emission (IIEE), which can be a significant contributor to electron emission at high energies or for small ions (such as helium). IIEE yield suppression has been observed for tungsten fuzz, but this effect has not been previously quantified experimentally or computationally.

A Monte Carlo model was used in Ref. 13 to study the effects of surface texturing on the SEE yield by simplifying the surface geometry into a section of a repeating pattern. The model presented in this work also uses a particle pushing technique, along with collision detection algorithms, to track ions and emitted electrons. Because IIEE analytical models are not as well developed as for SEE, the emission yield is empirically derived from experimental measurements from the literature. The emission characteristics (i.e., emission angle and energy), however, are obtained from the theory. Figure 1 schematically shows the modeling approach. Incident particles are pushed until colliding with a surface (i.e., the underlying substrate or a fiber), a number of electrons are generated at the point of collision, and once all incident ions have been lost, the emitted electrons are tracked until escaping or being absorbed by a neighboring surface. Because the sheath thickness of typical plasma devices (e.g., for EP and fusion) is much larger than the characteristic fiber lengths of the surfaces studied in this work, the effects of the electric and magnetic fields can be safely neglected. Hence, the ions are...
injected into the computational domain through the top boundary (a distance above the surface layer) and pushed ballistically. Unlike the SEE model, the incident ions and emitted electrons are assumed to be absorbed after impacting a surface, and secondary electrons are neglected due to the low incidence energy of electrons emitted by ion bombardment.

Accurately representing complex surfaces is paramount to successfully predicting geometric effects on the electron emission yield. Vertical pillars have been previously used to parametrically study yield suppression from carbon velvet; however, SEM images show two distinct apparent geometries when viewed from the top and profile directions, as shown in Fig. 2. This C velvet sample was engineered by Energy Science Lab, Inc. (see Ref. 17). Looking from the top, the surface can be modeled as sparsely distributed slanted fibers, approximately 50 μm apart at about 30°, on average, to the substrate. From the profile view, it is estimated that the fibers are approximately vertical and closely packed, with a separation distance of about 14 μm, near the substrate. Both geometries are studied in this work. For simplicity, for the slanted fiber geometry, the reference plane is rotated so that the substrate and particles are angled, while the fibers are held vertical.

Tungsten fuzz is modeled as a cagelike geometry of intertwined horizontal and vertical fibers. An SEM top view image of the fuzz surface, fabricated at MIT by exposing W to 60 eV He ions at 1270 K (see Ref. 15), is shown in Fig. 3. This geometry is also in agreement with other top and cross section SEM images of tungsten fuzz, as seen in Refs. 16 and 18 and is qualitatively similar to the overlapping

FIG. 1. Flowchart for the IIEE model.

FIG. 2. Carbon velvet SEM images from (a) top and (b) side views and representative (c) 30° slanted and (d) vertical fiber geometries.
ellipsoids used by Klaver et al. The W fuzz fibers are cylindrical, with 12.5 nm in radius and 200 nm in length. In order to maintain the correct fiber density, the fibers are spaced 200 nm apart and 5 horizontal fibers are used on each side of the rectangular computational domain.

As shown in Fig. 4, the emission of electrons due to ion bombardment is typically categorized into potential and kinetic emissions, which depend on different mechanisms to eject the electrons. While potential emission relies on resonance or Auger neutralization, kinetic emission occurs through direct transfer of energy through collisions. Several approximations have been suggested for the yield from each type of electron emission. However, because surface geometry effects on the electron emission yield are agnostic to the ejection mechanism, the two types of emission are not differentiated in this work. Hence, the total emission yield at normal incidence is obtained semiempirically by fitting exponential terms, as will be discussed later. The yield is then corrected for the incidence angle by dividing by the cosine of the incidence angle, $\gamma(\theta) = \gamma(0) / \cos(\theta)$.

When ions collide with surfaces, emitted electrons are seeded with random emission energies and directions. These emission characteristics must satisfy an angular cosine distribution and an energy distribution dependent on ion and surface properties and incident energy and direction. At the incident energies studied in this work, the electrons are predominantly emitted at energies well below 50 eV, with the most probable energies in the 2–4 eV range. Thus, secondary electron emission is neglected and the model becomes independent of the emission energy. For simplicity, all electrons are assumed to be emitted with an energy of 3 eV in the model.

When an ion impacts a surface, the number of electrons that are emitted is calculated using a Poisson distribution with the yield set as a distribution average. More complex distributions, such as Polya and others empirically derived, have a negligible effect on the results since the emitted particles would still average to the yield over a large number of incident ions,

$$P_n = \frac{\gamma^n e^{-\gamma}}{n!},$$

where $\gamma$ averages out the distribution to the correct emission yield and $n$ is the number of emitted electrons.

The model is first validated using data from Patino and Wirz. The fibers are measured to be approximately 2.6 \(\mu\)m long, with a 6.8 nm diameter. The IIEE yield from flat graphite is obtained by a least squares curve fitting to Xe\(^+\) on C yield data, as shown in Fig. 5(a),

$$\gamma = 12.45 - 10.11e^{-E_i/649\text{ keV}} - 2.34e^{-E_i/29\text{ keV}},$$

where $E_i$ is the ion incident energy, in kilo-electron-volt. Using this fit, Fig. 5(b) shows the results of modeling the carbon velvet as both slanted and vertical fibers (as shown in Fig. 2). The results from both geometries agree well with the data, with the slanted fiber case, resulting in a higher yield, as expected by the increase in the net yield due to a higher angle of incidence.

Similarly, flat tungsten data from Refs. 26 and 27 is fitted using exponential terms, resulting in

$$\gamma = 4.03 - 2.22e^{-E_i/127\text{ keV}} - 1.68e^{-E_i/16.2\text{ keV}} + 0.17e^{-E_i/441\text{ eV}}.$$
an estimated yield from the work of Hollman et al.\textsuperscript{28} In that work, the yield was approximated by assuming a reduction in the SEE yield taken from the literature and fitting the calculated current to experimental measurements. In contrast, the reduction in the IIEE yield from the model is directly obtained from simulations of the geometric trapping of emitted electrons and agrees with observations from Ref. 13 (for SEE yield reduction from W fuzz). The results shown in Fig. 6(b) show that the IIEE yield from W fuzz is independent of incidence angle across the range of $0^\circ$–$60^\circ$. This agrees with previous observations for W fuzz SEE behavior at $0^\circ$–$45^\circ$.\textsuperscript{15} An important result from the model is shown in Fig. 7, where the collision heatmaps show that the increase in the gross IIEE yield with incidence angle (for instance, for flat surfaces) is balanced by a roughly equal increase in trapping by the horizontal fibers, thereby eliminating the dependence of the yield on incidence angle for fuzz. Such independence is not strictly a property of all structured surfaces, but rather it is unique to certain structures, such as W fuzz.\textsuperscript{15} As a result, one may conclude that this unique angular independence is facilitated by the horizontal fibers for this geometry. Angular independence may be particularly important for highly magnetized plasmas, where high angular incidence of plasma species may predominate at plasma-facing surfaces.

The model presented in this work accurately simulates the reduction in the ion-induced electron emission yield from textured surfaces due to trapping of emitted electrons. The mechanisms that lead to this effect have been shown to be strongly dependent on the surface’s geometry and are relatively agnostic to the emission physics. The first empirically derived yield curves are formulated for flat graphite and tungsten for a wide range of ion incidence energies. Simulations of emission from carbon velvet using slanted and vertical fiber surface representations agree well with experimental data within the expected error and modeling uncertainty. The nanoscale tungsten fuzz results show that the reduction in the yield from the cage geometry is
FIG. 7. Emitted electron collision heatmaps for (a) 0° and (b) 45° ion incidence angles. The emission yield from the cage-like geometry is maintained independent of the incidence angle by increased trapping at higher incidence angles, as seen in the higher density of collisions in (b).

predominately facilitated by the horizontal-oriented fibers. This nature of trapping leads to an independence to primary electron incidence angle for IIEE, and the collisional maps show direct evidence of this W fuzz property, which was previously reported.13

Understanding the IIEE characteristics for complex surfaces will help with future efforts to design and characterize surfaces that can improve the performance of EP devices and tokamaks (where self-generated nanoscale W fuzz has been observed to naturally form). Furthermore, future designs of complex surfaces, such as foams and microarchitected dendritic surfaces (such as micro-pear or capped nodule texturing), can be simulated with this model to predict their influence on the performance of future plasma devices.29

This work was funded by the U.S. Air Force Office of Scientific Research, Grant Nos. FA9550-14-1-0317 and FA9550-16-1-0444, and by the Henry Samueli School of Engineering and Applied Science, University of California, Los Angeles.

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