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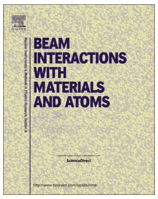

Electron transmission through a macroscopic platinum capillary

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ABSTRACT

We present simulations for electron transmission through a platinum macrocapillary (diameter $d = 3.3$ mm, length $l = 48$ mm) using classical transport theory. Both elastic and inelastic scattering events of primary electrons colliding with the inner wall of the capillary are taken into account. We also model the generation and transport of secondary electrons inside the material. We find excellent agreement of our simulated electron-energy spectra with recent experimental data for 200 eV primary electrons.

1. Introduction

In 2002 a report on deflection of highly charged ions (HCI) along the axis of insulating capillaries with sub-micrometer diameter *without* change of the initial charge state [1] initiated a series of experimental and theoretical studies on this so-called guiding effect. The experimental findings so far are consistent with the picture of HCI being Coulomb-deflected by charge patches on the inner capillary wall. A dynamical equilibrium is established between impact of HCI and depletion of the deposited charges due to the small conductivity of the target material [2,3].

A completely different mechanism was found to become active for the deflection of electrons in capillaries [4–8]: as the impact of an electron on the surface may lead to positive charge-up due to the emission of secondary electrons and, consequently, to attraction of subsequent projectiles towards the capillary wall rather than deflection by the Coulomb field electrons may also undergo a sequence of elastic and/or inelastic scattering processes at the surface and inside the capillary material resulting in many transmitted particles having suffered energy loss and in the production of secondary electrons which may also reach the capillary exit. As these processes do not depend on the conductivity of the target material it was predicted that also metallic capillaries should have the ability to redirect electrons with surface scattering being the only remaining deflection mechanism.

Recently, Milosavljevic et al. [9] have performed experiments on 200 eV electron transmission through a macroscopic platinum capillary (diameter $d = 3.3$ mm, length $l = 48$ mm). They found an exponentially decreasing transmission rate for tilt angles up to $\psi = 12^\circ$. For tilt angles $\psi \gtrsim 4^\circ$ the tube was not transparent geometrically. As for insulating nano- and microcapillaries [4,5] the energy spectrum of transmitted electrons showed strong contributions from inelastically scattered electrons.

In the present work we model this experiment and calculate energy spectra of 200 eV electrons incident on a platinum capillary using a classical trajectory Monte-Carlo (CTMC) simulation. Both elastic and inelastic collision events are taken into account upon impact of the electrons on the inner wall of the capillary. We also simulate the trajectories of secondary electrons generated in inelastic scattering events.

2. Theory

Transport of particles through materials is governed by the doubly differential cross sections for elastic scattering off the target constituents and for inelastic processes involving the excitation of the target and the energy loss of the primary particle. From the cross sections the mean free path is derived, i.e., the average distance between subsequent scattering events (for details see, e.g., [10–12]). Here, the doubly differential elastic cross section

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$\partial^2\sigma_{\rm el}(\theta,E)/\partial\theta\partial E$ is calculated in the static field approximation with non-relativistic Schrödinger partial wave analysis [13]. For the description of inelastic scattering cross sections we use the dielectric response formalism [14] based on analytic expansion of the momentum (q) and energy (ω) dependent dielectric function $\varepsilon(q=0,\omega)$ (from optical data) into the $q-\omega$ plane [15,16]. The bulk energy loss function is then given by Im$[-1/\epsilon(q,\omega)]$ and the surface loss function by Im$[-1/(\epsilon(q,\omega)+1)]$ (for a comprehensive review on the theory see, e.g., [17] and references therein) which, in turn, allow for the determination of associated cross sections and mean free paths. The dielectric function of Pt is generated following the prescription of Werner et al. [18,19]. This procedure accounts for the electronic structure of the target while underestimating the production of electron–hole pairs in the free-electron like part of the target's density of states (DOS). In the present case this approximation is justified by the small DOS of (free-electron like) s-electrons as compared to the DOS of d-electrons [20].

3. Results and discussion

The initial conditions for the CTMC simulation are chosen as to match the experimental conditions of [9]. Within the capillary electrons follow straight-line trajectories. Upon impact, they are deflected due to elastic or inelastic scattering events and may, possibly after additional impacts on the capillary wall, eventually exit the capillary. If secondary electrons are generated along the trajectory of the primary we follow their trajectories as well with the position of the inelastic scattering event as their starting place. The initial momentum is given by the energy loss of the primary, $p=\sqrt{2\cdot\Delta E}$, the initial direction of motion is chosen randomly. Finally, the energy of all electrons (primaries and secondaries) reaching the exit opening of the capillary determines the total energy spectrum of our simulation which can be compared directly with experimental data.

Fig. 1 shows energy spectra of 200 eV electrons which have undergone from 1 up to 5 impacts on a Pt surface. To simulate the response of the surface to electrons incident under a small angle (6° with respect to the surface) we use the surface loss function to compute the spectrum. In the spectrum for only one impact (note that the trajectory within the target material may involve multiple elastic and/or inelastic scattering events before the electron eventually leaves the surface) signatures of elementary excitation processes (e.g., surface plasmon excitation) from one or two inelastic scattering events are clearly visible. These features are washed out with increasing number of impact events leaving a spectrum dominated by low-energy secondary electrons after multiple impacts.

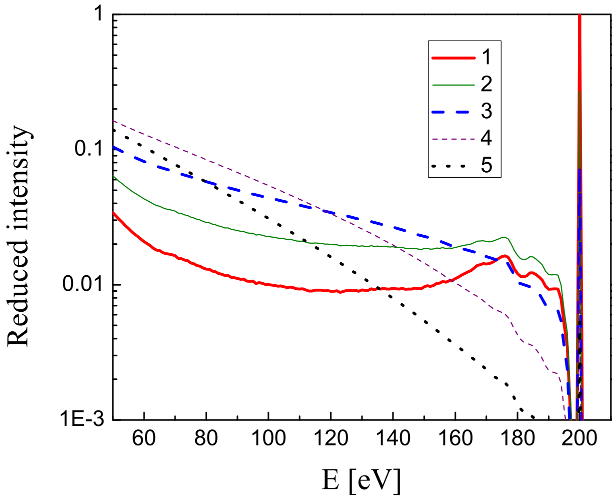

Fig. 1. Calculated kinetic energy spectrum of electrons after 1 (red solid thick), 2 (green solid thin), 3 (blue dashed thick) 4 (purple dashed thin), and 5 (black dotted) impact events on a Pt surface. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

Representative for all calculated energy spectra we compare our results with experimental spectra recorded for 200 eV electrons incident on a macroscopic Pt capillary tilted by $\psi=6^\circ$. The inner diameter of the capillary was $d=3.3$ mm and its length $l=48$ mm. As the experimental beam divergence Δ is unknown to us we vary Δ from 0° up to 5°, typical experimental values should not exceed $\lesssim 2^\circ$. We find the results to be rather insensitive to the value of Δ (see below).

At low electron energies and for gracing incidence conditions or, equivalently, small tilt angles ψ it is expected that the dominant excitations in electron-surface interactions originate from the surface region. We therefore use in our simulation the surface loss function to calculate the energy distributions of electrons backscattered from the Pt surfaces. 10^7 electron trajectories were started generating the total energy spectrum of transmitted electrons composed of primary and secondary electrons.

The number of deflections off the inner capillary wall strongly depends on impact parameter (entrance point into the capillary), tilt angle ψ, and divergence Δ. This can be easily illustrated for the case considered here ($\psi=6^\circ, \Delta=0^\circ, 1^\circ, 3^\circ$ and 5°, respectively) using straight-line trajectories specularly reflected from the capillary walls (Fig. 2).

We find trajectories which suffer more than 5 impacts on the inner wall of the capillary before they reach the exit surface. Almost 30% of the trajectories are deflected only once, $\sim 50-60\%$ undergo 2 deflections. In our simulation off-specular scattering is taken fully into account but does not change the number of impacts per trajectory much. However, boundaries between regions associated with specific numbers of impact events are smeared out, an effect similar to assuming a larger beam divergence (see Fig. 2).

In a simplified picture, the total spectrum is now composed by the sum of the spectra for 1 to 5 impacts shown in Fig. 1 weighted by the areas of the entrance opening corresponding to 1 up to 5 impacts on the surface (Fig. 2), respectively.

The results of the complete simulation are shown in Fig. 3 for various values of the divergence $\Delta\leqslant 5^\circ$ together with the experimental data points from [9]. For comparison we also reproduce the spectrum for single impact on a Pt surface. All spectra have been normalized to the intensity at 175 eV. It is evident that multiple impact events have to be accounted for in order to reproduce the experiment with a high degree of agreement. We furthermore notice the insensitivity of the spectra to the initial beam divergence. This can be readily explained by the wide distribution of exit angles of electrons after impact on the surface randomizing the angle of incidence for subsequent impacts. Already after the first scattering event the ensembles of trajectories for $\Delta=0^\circ$ and $\Delta\leqslant 5^\circ$ are nearly indistinguishable. Multiple impacts completely equalize the distributions.

4. Conclusion

We have presented classical trajectory simulations of the transmission of electrons through a macroscopic Pt capillary with 200 eV primary kinetic energy and 6° tilt angle of the capillary. The spectra were computed in the energy range between 50 eV and 200 eV. Both elastic and inelastic scattering of primary electrons colliding with the inner Pt surface as well as secondary electron emission from the capillary wall are taken into account. Near

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