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Charging dynamics in electron transmission through Al_2O_3 capillaries

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ABSTRACT

We have measured the transmission of low-energy ($E = 250$ eV) electrons through insulating Al_2O_3 nanocapillaries. We find that transmission at the incident energy is quickly suppressed with increasing tilt angle ψ of the capillary axis relative to the incoming electron beam while inelastic transmission becomes more important. For small angles of incidence charging dynamics lead to a decrease of total transmission (elastic and inelastic) with time. Our results are interpreted on the basis of a microscopic model for the electron transport within the capillary including also close interactions with the capillary wall.

1. Introduction

Shortly after guided transmission without change of the initial charge state of slow highly charged ions (HCI) through PET nanocapillaries has been discovered [1], possible applications of this effect (beam focusing, collimation, and deflection without electrical fields) have triggered a variety of experiments using other target–projectile combinations (e.g. [2–6]). The intuitive explanation in terms of charging of the inner wall of the capillary followed by projectile deflection by the Coulomb mirror without close interaction with the capillary wall [1] was quantitatively verified by a microscopic simulation invoking a diffusion model for charges deposited on the inner capillary wall after ion impact self-consistently coupled to the determination of projectile trajectories in the Coulomb field of the charged capillary material [7,8].

When using electrons instead of HCI, however, simple explanations fail for several reasons: on the one hand, a dominant fraction of electrons escaping the trajectory have energies smaller than the incident energy E_0 in clear contrast to the picture of (almost) loss-free reflection at large distances above the surface, on the other hand, electrons do not change their charge state and thus a clear distinction between transmission of the original projectiles (primaries) and emission of electrons set free upon impact of primaries on the capillary wall (secondaries) does not exist. Furthermore, secondary electron production also implies that surfaces can be, dependent on energy and angle of the primaries, positively charged [secondary electron emission (SEE) coefficient larger than 1] thereby *attracting* rather than deflecting subsequently arriving electrons.

In this manuscript we investigate the time-dependent transmission of 250 eV electrons through alumina capillaries and model electron dynamics in a microscopic model including a transport simulation for electrons within the capillary material. After an (almost) immediate onset of transmission, charging of the inner wall leads to a reduction of transmission.

2. Experiment

Our experimental setup (Fig. 1) has been described in detail elsewhere [9,10]. We therefore restrict ourselves to a short review of its most important features. An electron beam with electron energies between 100 and 350 eV (energy spread of about 0.5 eV) is directed onto a nanoporous Al_2O_3 membrane featuring a well-ordered matrix of capillaries with diameters of 270 nm and a length of 15 μm. The nanochannels array was produced using the self-ordering phenomenon during a two-step anodization process of a high purity (99.999%) 0.5 mm thick aluminium foil [11]. The intercapillary distance is about 450 nm and the calculated geometrical transparency is about 28.5%. Twenty nanometres thick metal layers are deposited on the front and back sides of the membrane to avoid charging of the target by electrons not entering any capillary. Position and tilt angle of the target can be adjusted by suitable manipulators. The energy of electrons escaping the backside of the membrane is analyzed using a double-cylindrical mirror analyzer before the particle is detected by a channeltron. The energy spectra

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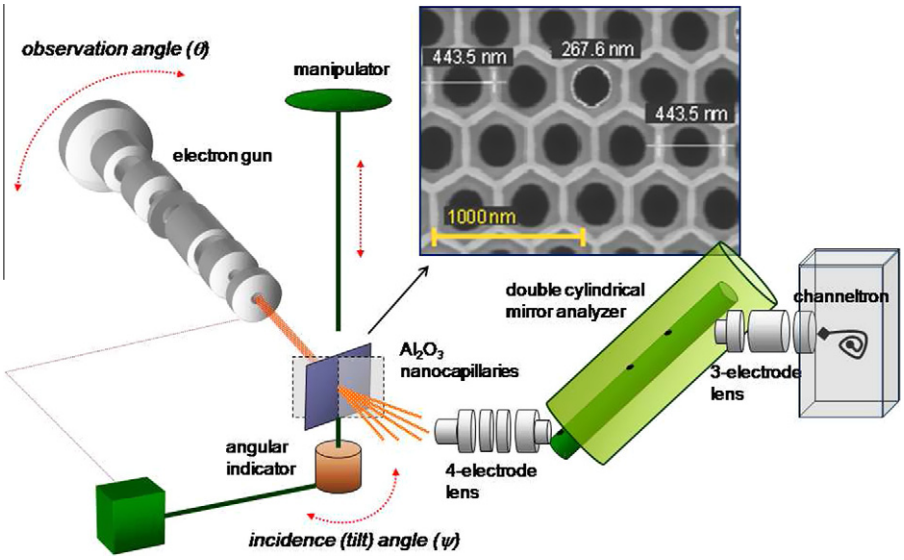

Fig. 1. Experimental setup used in the present work. Electrons produced by the electron gun are directed on a nanoporous alumina membrane. Electrons escaping the target are energy-analyzed. The inset shows a SEM image of the top surface view of the nanochannels array with about 270 nm capillary diameter (see [10] for more details).

were measured in the constant pass-energy mode of the analyzer, with the overall resolution of about 1.5 eV (full width at half maximum-FWHM). The used incident beam current was typically 10 ± 1 nA and down to a few nAs for some measurements of transmission dynamics. The base pressure in the experimental chamber was about 3×10^{-7} mbar.

A typical result of energy spectra is shown in Fig. 2 for 250 eV electrons with angles of incidence and observation $\psi \approx \theta \approx 0^\circ, 6^\circ, 9^\circ$. Even for $\psi = 0^\circ$ we find, apart from a sharp peak at the projectile energy E_0 which is expected for electron incidence parallel to the capillary axis, broad features at lower energies as also observed by Das et al. [12] for electron transmission through PET capillaries. Such structures can only be explained by inelastic scattering events in direct interaction with the inner capillary wall. For larger tilt angles the elastic peak is reduced while the features at smaller energies become more prominent.

These findings are in strong contrast to HCI transmission through insulating nanocapillaries where energy loss is not observed as the distance of closest approach to the surface for transmitted projectiles is sufficiently large as to prevent charge exchange at the critical distance of first electron transfer from the target material to the projectile. A rough estimate for the distance from the surface for classically allowed electron transfer over the potential barrier separating HCI and surface is given in atomic units by $d_c \approx \sqrt{2Q}/W$ where Q and W are the ions charge state and the work function of the target material, respectively [13]. For typical charge states of $Q \sim 10$ and workfunctions around $W = 10$ eV we find $d_c \approx 6.5$ Å and, as a consequence, an upper bound for the integrated energy loss ΔE along the trajectory of less than 1 eV [14] corresponding to $\Delta E/E$ well below 10^{-3}.

The well-established model for HCI transmission through insulating capillaries can therefore not be applied to our experiment and has to be extended to account for interaction processes taking place at and below the surface.

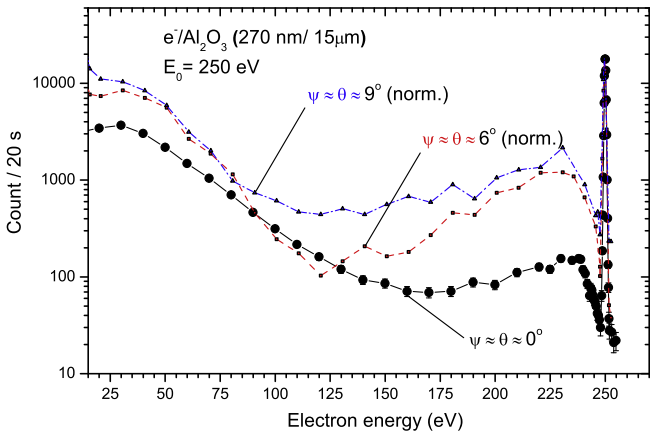

Fig. 2. Experimental energy spectra of electrons escaping alumina capillaries; projectile kinetic energy $E_0 = 250$ eV; angles of incidence (tilt) and observation angles are $\psi \approx \theta \approx 0^\circ$ (circles), 6° (squares), 9° (triangles). The curves for tilt angles of 6° and 9° are normalized to the maximum of the elastic peak by factors of 12 and 36, respectively.

3. Electron-transport model

In our model of HCI transmission [7] the charge at the surface was increased by the ions charge state Q once the projectile came closer to the surface than d_c. By contrast, for simulating transmission of electrons all interaction processes occurring after electron impact on surfaces (Fig. 3) have to be included [15]. The trajectory of the incoming electron is influenced by the Coulomb fields F_C of the charged surface (which can be both positive or negative) and its own dynamical image charge F_{im} (which is always attractive but weak at high projectile speeds). Furthermore, the response of the target material to the external charge leads to a friction force F_{fric} which decelerates the electron. Upon impact on the surface the electron can either be coherently and elastically reflected by the (attractive) potential of the surface, a process which contributes at small perpendicular velocities as used in our experiment, or it can penetrate the material initiating a collision cascade involving elastic large-angle scattering at atomic cores as well as small-angle scattering due to inelastic losses from scattering events at electrons in the target. The coherent backscattering rate was estimated using the self-consistently determined surface potential from a density-functional theory calculation for crystalline alumina. Upon penetration of the surface the energy lost in scattering events along the trajectory is transferred to low-energy secondary electrons which may also escape the surface and