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A Study of the Transmission of 10-keV Electrons through a Ceramic Macrochannel

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Abstract—Transmission of 10-keV electrons through a ceramic macrocapillary in the geometry, where the channel axis is oriented parallel to the incident-beam axis, has been studied experimentally. The current and energy spectrum of electrons passing through the channel have been measured depending on the incident beam current and the channel irradiation time. It is demonstrated that the transmission of electrons through a sample depends on the time that has passed after the formation of a conducting carbon deposit on the inner surfaces of both end faces of the channel.

Keywords: electron beam, dielectric channel, characteristic radiation, time dependence, guiding.

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The possibility of controlling beams of charged particles using dielectric channels (guiding) is an urgent problem in view of potentially designing inexpensive autonomous control and focusing devices. Currently, experiments involving ions with an energy on the order of several MeV are aimed at application of micrometer radiation for analysis of materials, surface modification, cellular surgery, etc. [1]. Such studies for electron beams are under way.

The results of the first investigations of the possibility of guiding nonrelativistic electrons with energies in the range of 200–1000 eV using dielectric channels were published in 2007 [2, 3]. Electron beams were transmitted through nanochannels of membranes made of aluminum oxide [2] and polyethylene terephthalate [3]. Guiding of electrons could be observed at tilt angles of the channels up to 10°–12° with respect to the axis of the incident electron beam. Guiding of electrons using channels with various sizes and configurations was investigated in a further series of experimental studies [4–8]. To date, the obtained results do not make it possible to draw unambiguous conclusions about the mechanism of this process. In particular, analyses of the time dependence of electron transmission through dielectric channels yielded that, in some experiments, transmission of electrons through a channel at different tilt angles with respect to the incident axis began instantaneously [2, 6, 7]; i.e., electron scattering from surface atoms can serve as the guiding mechanism. However, it was shown in other studies [3–5] that there is a time delay, which is required for charging insulator walls, before the instant when the channels began to transmit current; in this case, the guiding mechanism can be formation of self-consistent charge distribution on the inner channel wall.

In this Letter, we report the experimental data on the time dependence of transmission of 10-keV electrons through a ceramic (ZrO_2) macrocapillary. This material was chosen because of its high radiation resistance, high electrical resistance ($>10^{14}$ Ω cm), mechanical strength, and relative simplicity of sample reproduction. The inner diameter and length of the channel are 1.5 and 20 mm, respectively.

The scheme of the experiment is shown in Fig. 1. The experimental setup was described in more detail in [8].

An electron beam generated by electron gun *1* passes through system of electromagnetic lenses *2* and collimator *3* with a diameter of 1 mm. Formed beam *4* is incident on the input of channel under study *6* fixed in holder *5*. The channel input is covered by a metal grounded mask with a millimeter hole before the sample. The mask screens the channel end face, thus preventing channel cutoff by the normally incident beam electrons. The current of the primary beam in the

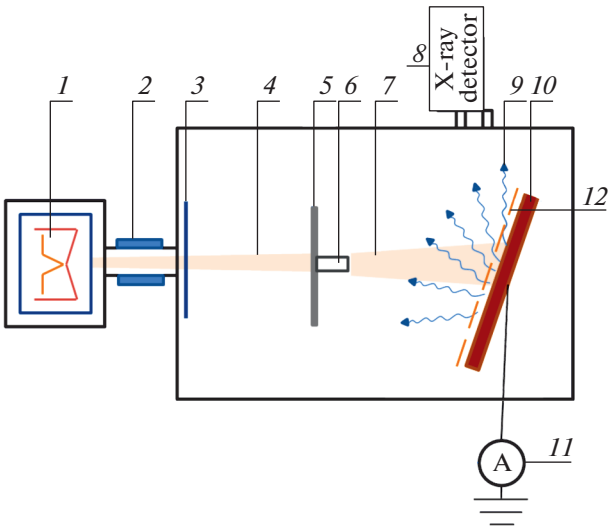

Fig. 1. Scheme of the experiment: (*1*) electron gun, (*2*) system of electromagnetic lenses, (*3*) collimator (∅1 mm), (*4*) accelerated electron beam, (*5*) holder with a grounded mask, (*6*) sample under study, (*7*) electron beam passed through the sample, (*8*) X-ray detector, (*9*) radiation generated by electrons hitting the copper plate, (*10*) copper plate, (*11*) amperemeter, and (*12*) brass grid with applied voltage of 400 V.

channel was measured through an additional hole (1 mm in diameter) in the mask.

Having passed through the irradiated channel, electrons *7* hit the at copper plate *10*. The spectrum of radiation generated in the plate is recorded on an XR-100SDD semiconductor solid-state detector *8*. The spectrum was measured to estimate the fraction of beam electrons that lost less than 1 keV. The algorithm of this estimation was described in detail in [9]. The current of the passed (or incident) beam is measured simultaneously using Keithley 6482 picoammeter *11*. Secondary electrons emerging from the copper plate are suppressed by brass grid *12* with applied voltage of 400 V placed directly before the plate. The experiment was carried out in vacuum at the residual pressure of about 10^{-6} Torr. All measurements were performed in the geometry in which the channel axis is oriented parallel to the incident-beam axis.

The dependences of the channel current on time and incident-beam current were measured as follows. During the first 5 min, the current of the beam passing through the mask hole was measured and the spectrum of radiation generated in the copper plate by arriving beam electrons was recorded. The holder with the sample was then shifted linearly so that the primary electron beam is fed to the input of the channel under study. The electron current transmitted through the channel and the corresponding spectrum were measured successively from six to eight times for 2 min with a pause between measurements of 10 s. The above-described measurements were performed for the incident-beam current in the range of 50–250 nA. It should be noted that the channel was preliminarily irradiated for 5 h before the described measurements. This time interval was chosen arbitrarily.

After the performed series of measurements, a carbon deposit was formed on the inner channel wall near the input end face. Despite the quite high vacuum in the target chamber, it always contains residual hydrocarbon molecules (e.g., molecules from adhesive materials (bilateral adhesive tape), which are used for fixing the sample, from nonmetallic goniometer parts, and often from possible grease or another organic surface contaminations). Under electron-beam irradiation of the sample, these molecules form a nonuniform carbon deposit on the irradiated surface, which can be observed by the naked eye. The presence of spots nonuniformly distributed on the inner channel surface was confirmed using electron microscopy, and it was determined that the carbon concentration in a spot is more than twice as high as that at an arbitrary point on the inner surface. It is of interest to see if one can affect significantly the channel transmission by forming a similar layer at the channel output end face. The channel was oriented so that the output unirradiated end face became an input, while the irradiated end face (with traces of a carbon film) became an output. The channel was left to lose its charge for 19 h because of the necessary technical operations and then (as in the initial orientation) was irradiated by a forward beam for 5 h. Similar (as for the direct channel orientation) measurements were carried out for several current values.

The experimental results are shown in Fig. 2. One can see in Fig. 2a that the fraction of particles passed through the channel decreases with an increase in the beam current in the channel. A similar situation is observed at an increase in the sample irradiation time. For the reversed channel orientation, the case is somewhat different (Fig. 2b). On the whole, the maximum channel transmission is retained at a level of 40%; however, in contrast to the initial channel orientation, the transmission increases with time at the incident-beam current of ~50 nA. At higher currents, the transmission for the reversed channel orientation also decreases with time; however, it remains rather high in comparison with the case of direct channel orientation.

Figure 3 shows the time dependences of the channel transmission and the fraction of electrons with an energy loss of no higher than 1 keV at an incident-beam current of ~50 nA. The data are presented for the (a) direct and (b) reversed channel orientations.

It can be seen that, in the case of a reversed channel, the transmission does not begin immediately, but gradually increases to some level, whereas in the initial orientation the channel begins to transmit current immediately and then is gradually cut off. The obtained time dependences of electron transmission

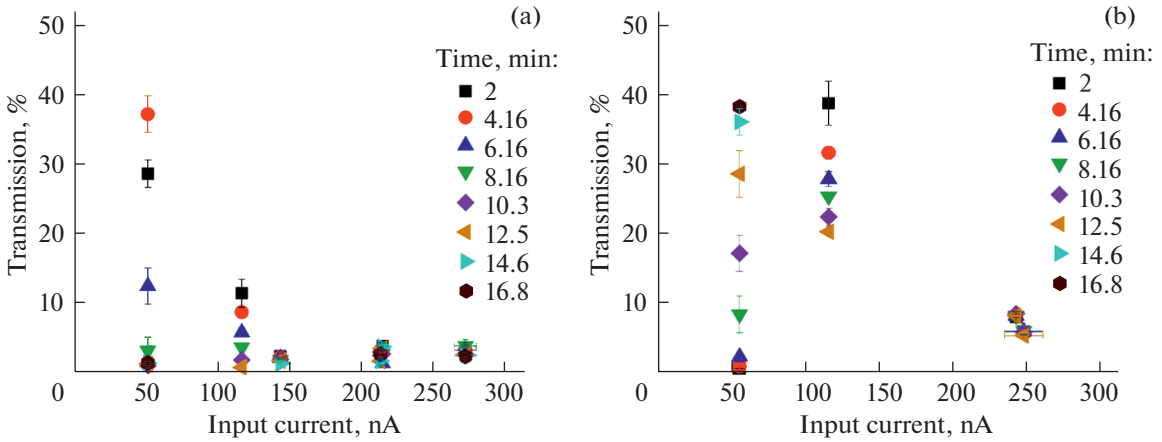

Fig. 2. Dependences of the channel transmission on the forward-beam current for different channel-irradiation times in the (a) direct and (b) reversed channel orientations.

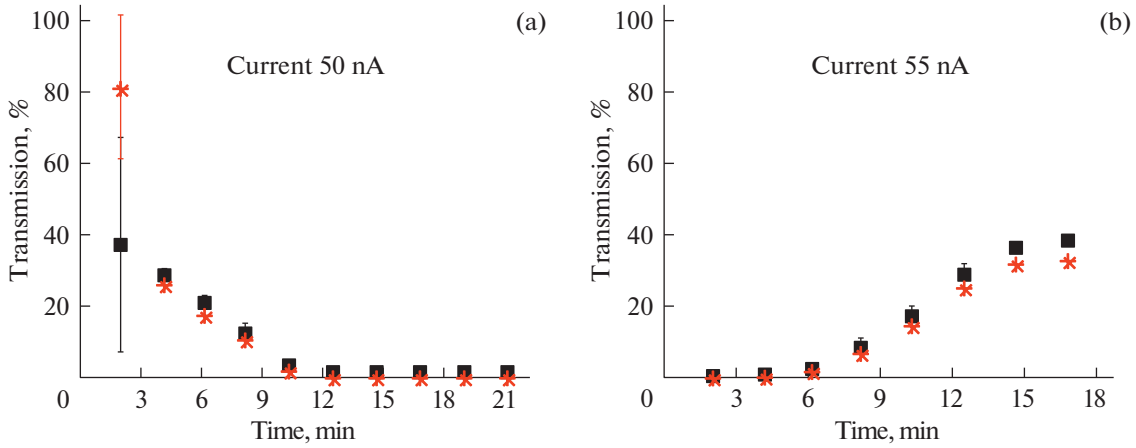

Fig. 3. Time dependences of the (squares) channel transmission and (asterisks) fraction of electrons with an energy loss of no higher than 1 keV for the forward-beam current of ~50 nA in the (a) direct and (b) reversed channel orientations.

through the channel favor the model of formation of a self-consistent charge distribution on the inner channel surface, which takes into account both surface charging and simultaneous leakage of a part of the charge (in the case of stable channel transmission). However, the found carbon fractions inside the channel should be taken into account at further development of the process model in view of their influence on the surface conductivity of the insulator.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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