XVII Symposium on Condensed Matter Physics SFKM 2007

Program and Contributed Papers

SFKM

September 16-20, 2007, Vršac, Serbia

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Editors:
R. Zikic
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Published by: Institute of Physics, Belgrade

CIP – Katalogizacija u publikaciji
Narodna biblioteka Srbije, Beograd

538.9(082)
538.9(048)

Symposium on Condensed Matter Physics (17 ; 2007 ; Vršac)
Program and Contributed Papers / XVII Symposium on Condensed Matter Physics - SFKM 2007, September 16-20, 2007, Vršac, Serbia; [editors R.[Radomir] Zikic … et al.]. – Belgrade : Institute of Physics, 2007 (Beograd : Tonplus). XIV, 240 str. : ilustr. ; 25 cm

Tiraž 200. – Bibliografija uz pojedine radove.

ISBN 978-86-821-21-2
1. Žikić, Radomir
a) Fizika kondenzovane materije – Zbornici
b) Fizika kondenziovane materije – Apstrakti
COBISS.SR-ID 143392012

Guiding of Electrons by Al_2O_3 Nanocapillaries

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Abstract. We present an experimental investigation of guiding of low-energy electrons (≤ 350 eV) by insulating nanocapillaries with large aspect ratio (140 nm diameter and 15 μm length). The nanochannels array was prepared using self-ordering phenomena during a two-step anodization process of a high purity aluminium foil. Our recent results [A. R. Milosavljević et al, Phys. Rev. A **75**, 030901(R) (2007)] clearly showed the existence of a guiding effect for electrons, as found for highly charged ions [N. Stolterfoht et al, *Phys. Rev. Lett.* **88**, 133201 (2002)]. The guiding of the electron beam was observed for the tilt angles (the angle between the capillary axis and the electron beam direction) up to 12^o. As seen for the highly charged ions, the guiding efficiency was found to increase with decreasing the incident electron energy. However, the transmission efficiency appeared to be significantly lower than the one observed for HCIs and, moreover, the intensity of transmitted electrons significantly decreases with decreasing the incident energy. In this work we further investigate the electron guiding by highly ordered Al_2O_3 nanocapillaries, studying in more details energy loss spectra of transmitted electrons, the dependence of the width of the measured angular distributions on the tilt angle and the time dependence of the transmitted electron beam intensity.

INTRODUCTION

The transmission of charged particles through insulating nanocapillaries has attracted considerable attention in recent years since Stolterfoht et al. [1] reported an unprecedented experiment of transmission of 3 keV Ne^{7+} ions through nanocapillaries (100 nm diameter and 10 μm length) of highly insulating polyethylene teraphthalate (PET). Surprisingly, they found that majority of Ne^{7+} ions survived the surface scattering in their initial charge state, while the angular distributions of the transmitted highly charged ions (HCI) indicated propagation of ions along the capillary axis. This provided the evidence for the guiding effect, which was attributed to self-organized charge-up processes that inhibit HCI from hitting the capillary walls. Except for the PET nanocapillaries [1,2] (and references therein), measurements were reported on transmission of HCI through SiO_2 [3] and Al_2O_3 [4,5] nanocapillaries, as well. The

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experimental results are partially supported by a classical trajectory simulation that relates the microscopic charge-up to macroscopic material properties [6-8]. Besides the investigation of hollow-atom formation at large distances from the surface [9], the studies of capillary guiding might gain important information about the properties of the inner walls of the capillaries and for possible applications (e.g., manipulation of charged particles on the nanoscale [10]).

To the best of our knowledge, the investigation of the guiding effect has been mostly focused on the use of positive ions as projectiles, mainly slow (3–7 keV) HCIs and only very recently the first results were reported on guided transmission of electrons through insulating nanocapillaries [11,12]. The use of electrons further extents the investigation of guiding effect, considering opposite charge of the projectile and different charge/energy ratio.

EXPERIMENT

The nanocapillaries sample has been made in Louvain-la-Neuve. A detailed description of fabrication of Al_2O_3 nanocapillaries used in the present experiment has been given recently [4]. Briefly, a highly ordered hexagonally close-packed nanochannels array was prepared using the self-ordering phenomenon during a two-step anodization process of a high purity (99.999 %) 0.5 mm tick aluminium foil. To prevent a macroscopic charge-up of the target surface, the niobium layers of 20 nm thickness were deposited by dc-sputtering on both sides of the final well-ordered honeycomb membrane. The diameter of the used Al_2O_3 capillaries is about 140 nm, the intercapillary distance about 320 nm, while the length is 15 μm. The calculated geometrical transparency is about 8.4 %.

The experiment has been performed at the Institute of Physics, Belgrade using a modified cross-beam experimental setup, which was described in detail elsewhere [13]. The electron beam is produced by an electron gun, and a sample nanocapillary array was mounted on a target holder, allowing a change of the orientation of the capillary axis with respect to the electron beam direction. The base pressure in the experimental chamber was about $1x10^{-6}$ mbar. The transmitted electrons were focused into a double-cylindrical-mirror energy analyzer and detected by a single-channel electron multiplier working in single-counting mode. For each experimental point, the intensity was measured at the maximum of the elastic peak obtained in the energy loss mode. During measurements of the angular distributions, the incident beam current was about 14±1 nA. The radius and angular divergence of the incident electron beam were estimated to be 0.5–1 mm and 0.2° – 0.5°, respectively (see [13]), thus giving an estimate of 20–80 nA/mm^2 of the primary beam current density. The angular distribution of the primary beam was measured using the analyzer system as a Faraday cup and found to be about 1.8° (FWHM).

RESULTS

Fig. 1a shows measured intensities of the transmitted electron beam as a function of the observation angle, for a selected incident electron energy (E_0) of 290 eV and different tilt angles from about -3^o to 12^o (see inset of Fig 1b for definition of the observation and tilt angles).

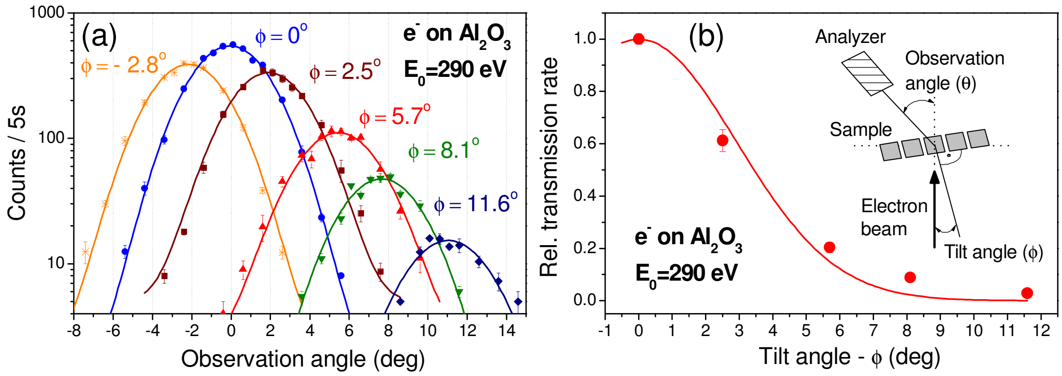

FIGURE 1. (a) Angular distributions of electrons transmitted through the Al_2O_3 nanocapillaries for the impact electron energy of 290 eV and different tilt angles (ϕ). ϕ-FWHM: 0^o-4.3^o, 2.5^o-4.2^o, 5.7^o-4.5^o, 8.1^o-4.5^o, 11.6^o-4.6^o. (b) Relative transmission as a function of tilt angle. Experimental points are fitted by the function: $f(\phi) = f(0)\exp(-\lambda \sin^2 \phi)$ [12]. The inset gives schematic representation of the experimental set-up.

The centroid of the peak formed by transmitted electrons shifts with changing tilt angle and it matches well with the tilt angle of the capillaries. Since the capillaries should be totally closed already at the tilt angle of about 1^o, the presented results clearly show an evidence of the guiding effect. Similar results were also obtained for other electron energies from 350 eV down to 200 eV (the lower limit being imposed by a low transmission) [12]. The relative intensity of transmitted current at the maximum is presented as a function of tilt angle in Fig. 1b. The experimental points are well fitted by an exponential law proposed in earlier work for HCI (see [12]). The recorded electron energy loss spectra suggest that majority of transmitted electrons undergo only elastic scattering inside the capillaries (Fig. 2).

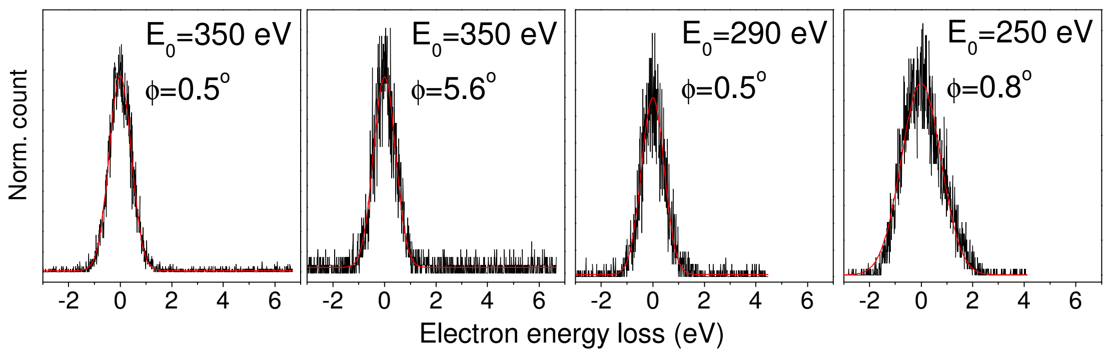

FIGURE 2. The energy loss spectra of transmitted electrons for different energies and different tilt angles (≈ observation angle). The experimental energy resolution was about 1 eV (1.8 eV for 250 eV).

In our measurements, the guiding was established almost immediately after the beam is turned on. More interestingly, for discharged capillaries, the measurement of the time dependence of the intensity of transmitted electrons shows a decrease (see Fig. 3).

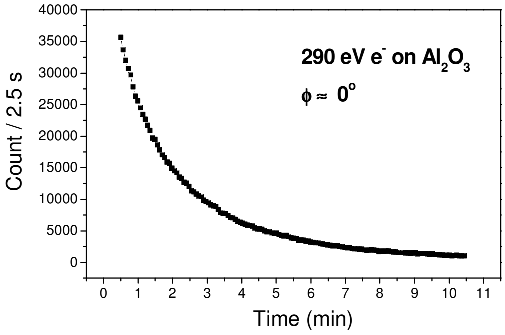

FIGURE 3. Time dependence of the intensity of transmitted electrons at E_0=250 eV and $\phi \approx \theta \approx 0°$.

To conclude, we have investigated transmission of electrons (200-350 eV) through insulating Al_2O_3 nanocapillaries. The obtained results confirm the existence of guiding effect, as found for HCI but also reveal some new features. Further experiments are carrying on to investigate electron guiding at even lower energies (below 100 eV).

ACKNOWLEDGMENTS

This work has been supported by MSEP of Republic of Serbia under project 141011 and by the Interuniversity Attraction Pole Program (P6/42) - Belgian State - Belgian Science Policy.

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