Transmission Electron Microscope as a Tool for Nanotubes and Graphenes Property Studies

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The knowledge of mechanical, electrical and thermal properties of nanotubes and graphenes, in particular, on the individual structure level, is of prime importance as far as their real integration into modern nanoscale devices is concerned. Until now, such property measurements have usually been carried out using the instruments (*e.g.* scanning electron- (SEM) and atomic force microscopes (AFM)) having no direct access to the nanotube or graphene internal structures. This has significantly decreased a value of data since the particular structural features of the nanostructures tested (which, in turn, determine the properties) have been unknown. Only recently, the projects on property measurements under ultimately high-spatial resolutions, natural to high-resolution transmission electron microscopes (HRTEM), have attracted full attention. In order to carry out such studies, special types of TEM holders with either scanning tunneling microscope (STM) or AFM capabilities have been designed. For example, such holders have been developed and commercialized by the "Nanofactory Instruments AB", Sweden.

In this presentation we demonstrate how the regarded *in-situ* techniques can originally be applied for the nanotube/graphenes property measurements and/or their on-demand three-dimensional nanomanipulations inside a TEM. The objects of interest within our Laboratory are diverse and include numerous inorganic nanotubes made of C, BN, ZnO with or without metal fillings, nanowires (Si, ZnS, GaN), nanobelts (CdS), nanothermometers (Ga@MgO, In@SiO_2), and "black" (*i.e.* C) or "white" (*i.e.* BN) graphenes. It is particularly noted that until the present work, apart from the case of standard multi-walled C nanotubes and C graphenes, most of the electrical and/or mechanical, and thermal characteristics of these individual advanced inorganic nanomaterials have remained unknown.

We are focusing on several practically important aspects as revealed by *in situ* TEM: (i) interactions of C nanotubes and graphenes with various metal electrodes under a current flow and subsequent Joule heating; (ii) bending and tensile strength of individual multi- and single-walled C and BN nanotubes, and corresponding graphenes; (iii) precise temperature measurements on nanostructures using multi-terminal electrical circuits created inside the STM-TEM holders; (iv) effects of different deformation modes on the electrical performances of nanoobjects; (v) field-emission from individual nanotubes and graphenes; (vi) complex nanostructure network soldering using nanomanipulations and in-tandem electron irradiations and electrical currents; (vii) metal phase transformations inside nanotube pressure vessels; and (viii) electron irradiation-induced doping recorded within ternary B-C-N nanosystems that allowed us to effectively create various nanoscale semiconductors with tunable bandgaps.

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