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Formation of surface nanostructures in interaction of highly charged xenon ions with nanolayers

This doctoral dissertation is devoted to the study of interactions of slow highly charged xenon ions (SHCI) with nanolayers. The aim of this dissertation is to determine the properties of nanolayers and to understand the mechanism of surface nanostructures formation in collisions of slow highly charged xenon ions with the surfaces of metallic nanolayers. The experiments were performed in the Surface Physics Laboratory of the Institute of Physics of the Jan Kochanowski University in Kielce. Gold, titanium and titanium dioxide nanolayers of different thicknesses (5-100 nm), deposited on three different substrates (silicon, quartz and borosilicate glass), unmodified and irradiated were investigated. To achieve the aim, the following tasks were completed:

- the physicochemical properties of nanolayers were determined using the following methods: X-ray diffraction (XRD), grazing incidence X-ray diffraction (GIXRD), X-ray reflectometry (XRR), spectroscopic ellipsometry (SE), and atomic force microscopy (AFM),
- on the basis of theoretical calculations and computer simulations, the benefits of using grazing incidence analytical techniques, i.e. GIXRD and XRR, were presented, in the context of the analysis of the substrate and deposited nanolayers,
- metallic nanolayers with well predictable properties and low roughness were modified with slow highly charged xenon ions,
- the experimental conditions under which permanent modifications occur on the surfaces of gold and titanium nanolayers were determined,
- a method for controling the SHCI beam profile was developed, which allowed to estimate the fluency of the ion beam used for irradiation of the nanolayers surface,
- a procedure for the analysis of the nanostructures on 3D images obtained by atomic force microscopy after irradiation on the nanolayers with the SHCI was developed,
- a statistical analysis of the height and volume of nanostructures formed after bombardment with slow highly charged xenon ions was performed,
- the influence of kinetic and potential energies of xenon ions on size of structures formed on the surface of gold and titanium nanolayers was investigated,
- the obtained results were compared with both experimental and theoretical data available in the literature.

The doctoral dissertation is experimental and contains 8 chapters. Chapter I presents the definitions of the nanolayer as well as a brief description of the properties and applications of nanolayers that were studied in the thesis. Chapter II is devoted to a detailed discussion of the physical basics of techniques used for investigation of the properties of nanolayers: X-ray diffraction (XRD), grazing incidence X-ray diffraction (GIXRD), X-ray reflectometry (XRR), spectroscopic ellipsometry (SE) and atomic force microscopy

(AFM). Chapter III begins with the description of the basic quantities characterizing slow highly charged ions. This chapter also discusses in detail the processes occurring during the interaction of a SHCI with a material surface. In the chapter IV the experimental system of the EBIS accelerator used for the production of SHCI is described. Chapter V presents the current state of knowledge in the field of interaction of highly charged ions with materials. The experimental results and their interpretation are presented in the last three chapters. Chapter VI contains theoretical calculations, simulations and measurement results for the nanolayers before irradiation with xenon SHCI. Chapter VII presents the experimental conditions in which the nanolayers were irradiated and the method of characterization of nanostructures formed on the surface of nanolayers. Chapter VIII contains the results of a series of experiments in which gold and titanium nanolayers were irradiated with xenon SHCI (in the range of charges from Xe^{15+} to Xe^{40+}). In these experiments, the efficiency of the nanostructures production process and the shape of the resulting nanostructures (pits, hillocks, craters) was investigated. In particular the influence of kinetic energy and the potential energy of ions on the shape and size of the produced nanostructures was determined. The work ends with a summary of the results obtained.

The thesis shows that the applied research methods can be used for comprehensive analysis of the properties of nanolayers as well as for the study of nanostructures formed after modification with SHCI. The most important result of the conducted research is the observation for the first time nanostructures created by xenon SHCI on the surface of gold and titanium nanolayers. This observation allowed for a better understanding of the mechanism of nanostructure formation on metallic surfaces. Theoretical calculations with the use of the micro-staircase model clearly showed that both the velocity of highly charged ions (and thus their kinetic energy) and ion potential energy have the influence on type and size of nanostructures obtained on metallic surfaces. Calculations with the use of the i-TS 3D thermal spike model qualitatively confirm the presented results and show that the potential energy of xenon ions affects the diameter of the molten area, and thus the dimensions of the nanostructure on the surface. The sizes of the obtained nanostructures on the surfaces of metallic gold nanolayers turned out to be consistent with experimental data and the MD simulations available in the literature for single ionized xenon.

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