JOINT INSTITUTE FOR NUCLEAR RESEARCH

D14-2005-183

As a manuscript
UDK 621.315; 536.372;
539.124

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INVESTIGATION OF SPUTTERING OF SOLIDS INDUCED BY SWIFT HEAVY IONS

Speciality: 01.04.07 — physics of condensed matter

Overview
of the Thesis for the Degree of Candidate of Physical-Mathematical Science

Dubna 2005

The work has been carried out at the Flerov Laboratory of Nuclear Reactions of Joint Institute for Nuclear Research, Dubna.

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The defense of the thesis will be carried out on “___ “_________2006 at “____” at the meeting of dissertation council D 017.01.05 at the Frank Laboratory of Neutron Physics and the Flerov Laboratory of Nuclear Reactions, JINR (141980, Dubna, Moscow Region, JINR, FLNR)

Thesis is indexed at the library of JINR

The Summary is distributed on “____”__________2005

The Scientific Secretary of Dissertation Council A.G.Popeko

The actuality of the problem

The study of materials in radiation environments gained particular significance after the arrival of nuclear reactors. Radiation has joined other hostile and severe environmental conditions facing modern engineering materials in many important technological applications.

Such applications that involve significant levels of radiation include: nuclear fission reactors, proposed fusion reactors, nuclear waste management, ion accelerators, and spacecraft. The types of radiation encompassing wide energy ranges and species such as; thermal and fast neutrons, light and heavy ions and energetic photons.

Most of the change experienced by materials is unfavorable for the performance of materials, justifying the influence of radiation being referred to as Radiation Damage. Extensive ongoing research are carried out to broaden the accumulated database of the behavior of materials in radiation environment, beside this applied work, extensive fundamental research on radiation effects has been pursued, because the bombardment of materials with energetic particles especially with high energy heavy ions, offer a unique method to produced athermally, controlled and large concentration of atomic order disturbance, both on the surface and of the bulk, the extent of the disturbance can be measured by some change in an important physical properties, especially surface and bulk mechanical properties changes which despite the wealth of accumulated information and proposed models are not so well understood.

These properties of the irradiated materials have received the most attention, were it had been identified as one of the most important design problem for the implementation of commercial fusion reactors.

In addition the primary recoiled spectra of ion irradiation can be systematically varied when by the appropriate selection of ion masses and energies, the predominant cascade energies of an irradiation can be varied from tens of eV's to hundred of keV's per a.m.u . The current ability of accelerators to deliver up to several tens of MeV/a.m.u, means that it is now possible to use well-defined parallel beams of ions which deposit huge energy densities into materials where linear electronic stopping powers can be up to 80 keV/nm, which far exceeds the nuclear stopping power, the exploration of the ions energy loss in this region, gives rise to several unexpected new and exciting phenomena as the production of latent ion tracks in dielectric and semiconductor materials and the inelastic sputtering with very high sputtering coefficients (sputtering yields).

In most cases, however, the microstructural and property evolution in these materials are determined by the outcome of a competition between a large number of microstructural and microchemical mechanisms, subsets of which often work in opposite to each other. The outcome can change in favor of one mechanism or subset of mechanisms over others in response to variation in environmental or material variables. In some cases, the dominant variable may be masked, or uncontrolled by other competing variables, exerting an influence on the investigation.

Therefore, if one desire to isolate and study the action of one particular mechanism, it is best to use pure metals or model alloys, thereby reducing the number of competing mechanisms. In the current study several pure metals, semiconductors and Highly Oriented Pyrolitic Graphite (HOPG) in addition to stainless steel alloy were chosen not only because of their technological relevance in fusion technology but also as represented models, to avoid the complex analysis problems which may arise from the composition and to simplify any theoretical applications of the results which can be extrapolated to the exploration of radiation-induced microstructural and mechanical change that have been observed in more simple metals or alloys of engineering importance. As far as the author's knowledge, this was the first time the investigated materials were subjected to the irradiation conditions and combination of ion species, fluences, and energies.

The application of swift heavy with the high level of inelastic energy loss for the study of radiation phenomena in condensed matter gave unique insights to observe a number of peculiarities in the damage creation processes which can not be explained from the point of view of traditional approach using the mechanism of elastic collisions.

During the last decades, extensive body of literature has accumulated, reporting different aspects of elastic sputtering phenomenon. Sputtering by ions is the erosion of solid surfaces during ion bombardment. Most studies were directed on the description of elastic (nuclear) sputtering under irradiation by low energy heavy ions. The theoretical aspects and cascade model of elastic sputtering are well developed and understood.

But during the last three decades, continuous scientific efforts were directed to investigate the phenomenon of inelastic sputtering. This field has begun by using the fission fragments to study the sputtering of various materials. During these studies several peculiarities of surface phenomena in metals, alloys, dielectrics, semiconductors and amorphous materials have been observed. Such as the high values of sputtering coefficients in dielectrics and small dispersed metallic targets with grain sizes less then 10 nm sputtering coefficients in this case were of two or three orders of magnitude higher then of the usual coarse-grained targets.

In general there exist few theoretical descriptions of the observed phenomena: the thermal spike model (in other words "hot track") and coulomb explosion double charged surface layer, the model of isolated grain, the "hot spot" model and some other combinations of these approaches. Unfortunately, the behavior of different materials with various properties under the irradiation by swift heavy ions is not yet clear.

The study of sputtering of solids under fission fragments initially and subsequently by using modern techniques of accelerated heavy ions showed that the sputtering processes don't agree with the elastic sputtering theory, whereby experimental observations are quite different than observations of solid sputtering observed by low energy ion irradiation.

These investigations of the effects of high energy heavy ions on surfaces has the great relevance because of the installation and commissioning in exploitation of the accelerators and ion accumulating rings of heavy ions with high energy, as well as, the study of determining the radiation resistance of construction materials, which are potential materials to be used in thermo-nuclear reactors.

Such technological problems require intensive fundamental investigations as the results presented in this thesis. The obtained results are very useful from both the fundamental physics of radiation damage and the applied applications point of views.

The purpose of the work undertaken in this thesis is to gain new insights and experimental results in the field of interaction of swift heavy ions with condensed matter, the study of the processes of radiation damage and of the influence of cumulative high damage levels on subsequent processes of sputtering. The investigations of the surface features and changes of the surface of metals, stainless steel, Highly Oriented Pyrolytic Graphite (HOPG) and silicon after swift heavy ion irradiation.

For the observation of the post-irradiation surface features, the main techniques used in this thesis were Scanning Electron Microscopy (SEM) and Scanning Probe Microscopy such as Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM).

The aim of the work

To investigate the effects of high electronic energy deposition by swift heavy ions on the surface properties of some technologically important pure metals and alloys and to determine the sputtering coefficients due to the high energy ion irradiations. The work is of important relevance for the development of high performance structural materials for the modern fission and future fusion reactors.

The scientific novelty

The sputtering coefficients of the investigated materials at high level ionizing energy loss were found to be very high (sometimes - in the range of 10^2-10^3 atom/ion). The sputtering coefficients values were also found to be profoundly dependent on the presence of defects in materials, and also strongly depend on initial microstructural conditions of surfaces. Sputtering at grain boundaries is very large compared to sputtering within the grains in polycrstalline metals.

In addition, observations were carried out on other microstructural surface changes and features of the investigated metals and alloys due to the effects of high electronic energy deposition.

The scientific value and practical relevance of the work

The results obtained from the current investigations, are of very significant relevance for the selection of structural materials for the fusion and fission reactors. Also the materials that show strong sputtering are not suitable for some technological applications, for example as materials in collective rings for heavy ions accelerators.

The main results obtained in thesis

Herewith, we formulate the following important results and observations.

1. The sputtering coefficients of polycrystalline and single crystalline materials by swift heavy ions in inelastic energy loss range which is less then threshold values were slightly different from that based on predictions of the cascade model.
2. The sputtering behaviors of single crystalline solids (metals, semiconductors) with structures close to perfect structure are in accordance with the cascade theory (sputtering coefficients about 1-3 atom/ion).

3. The grain boundaries, act as strongly defective zones. The sputtering at grain boundaries characterized by sputtering coefficients which are few orders in magnitude higher then the characteristic values predicted from the cascade model. The sputtering coefficients can reach more then 10^3 atom/ion.
4. The sputtering of metals (Ni, W, and Au) and chromium nickel stainless steel were studied and sputtering coefficients estimated using the *step* method for the measurements of sputtering coefficient for polycrystalline Ni.
5. The estimations of sputtering coefficient of strongly deformed gold sample were carried out. It was shown that the value of sputtering coefficient is high and comparable with the sputtering of coarse grain gold samples.
6. Sputtering of model crystals of Highly Oriented Pyrolitic Graphite (HOPG) was studied at various fluences under irradiation by ^{86}Kr and ^{209}Bi ions. It was shown the surface density of formed craters after irradiation by ^{209}Bi ions with very high level of inelastic energy loss has a value of only a few percent of the corresponding ion fluence. It means that sputtering in this case has a probabilistic stochastic character and can be explained by thermal fluctuation model.
7. It was shown that the surface of HOPG grain does not show any features after irradiation by ^{86}Kr ions. However the sputtering at grain boundaries was very strong.
8. The surface changes of silicon single crystal after irradiation by ^{86}Kr ions (energy was 253 MeV, fluence was 1-3 x10^{15} ion/cm^2) with high fluence were studied. The sputtering coefficient of the samples was estimated and compared to the elastic sputtering case of silicon (ions ^{40}Ar with energy 300 eV, fluence was 4,8x10^{17} ion/cm^2).
9. Generally, the reached conclusion from experimental research presented in the thesis is the following: inelastic energy loss of swift heavy ions has great influence on the sputtering of metals, HOPG and silicon single crystals particularly for crystals with high level of defect concentration.

10. The high value of sputtering coefficients for metals and some other materials indicates that surface conditions and sputtering are extremely important factors to account for in technological applications.

Fundamental results of the thesis submitted for defense

1. System of differential equations for the calculation of electron gas and lattice temperatures and numerical scheme of solving of the system of differential equations in the thermal spike model are obtained.
2. The sputtering coefficients of pure polycrystalline Ni and Au metals under the irradiation by ^{86}Kr with energy 253 MeV are measured.
3. The sputtering and surface features of high quality single crystalline tungsten, Highly Oriented Pyrolitic Graphite and silicon single crystals irradiated with high energy ^{209}Bi and ^{86}Kr were studied.
4. The surface features of chromium nickel stainless steels under irradiation by ^{86}Kr ions (with energy 253 MeV) were investigated and sputtering coefficient was measured.
5. It was shown that inelastic energy loss of swift heavy ions practically does not influence strongly on the sputtering of metals, HOPG and silicon single crystals with perfect structure while it is essential factor when crystals contain high concentration of defects.

The presentation of the work

The thesis results were reported and discussed on the following scientific conferences and seminars: IX(1999), X(2000), XI(2001), XII(2002), XIV(2004) and XV(2005) International Conferences "Radiation Physics of Solids" (Sevastopol, Ukraine); IIIth (1999), IVth (2001) and Vth (2003) Schools and Workshops on Cyclotrons and Applications (Cairo, Egypt), XVth (2001) and XVIIth (2005) International Conferences: "Ion-Surface Interaction" (Zvenigorod, Russia, 2001 and 2005); XIV International Conference on Physics of Radiation Phenomena and Radiation Material Studies (Alushta, Ukraine, 2004); V International Conference "Interaction of Irradiation with Solids" (Minsk, Belarus, 2003); "Structural basis of material modification by means of methods of non traditional technologies." (Obninsk, MNT-VII, Russia, 2003); Conference: "Influence of External Factors on Elemental Base of Apparatus for Aviation and Cosmic Techniques" (Korolev, Russia, 2003); Xth Jubilee Scientific-Technical Conference with the Participation of Foreign Specialists: "Vacuum Science and Techniques" (Crimea, Sudak, 2003); 35th International Conference on Physics of Charge Particle Interaction with Crystals (Moscow State University, 2005).

The results were presented and discussed on the scientific seminars of Flerov Laboratory of Nuclear Reactions (JINR, Dubna, Moscow Region, Russia), Tabbin Institute for Metallurgical Studies (Cairo, Egypt), Institute of Experimental and Theoretical Physics (Moscow, Russia), Nuclear Research Center (Cairo, Egypt) and some others relevant institutions.

Publications

The results of the work were published in 17 publications.

The structure of the thesis

Thesis consists on introduction, five chapters, conclusion, references and acknowledgment. Thesis volume is 180 pages, including 37 figures, 6 tables; the number of references is 160.

Contents of the thesis

The Introduction gives a detailed account of the actuality and the aim of investigation. The scientific novelty and practical validity of the results were presented and the basic results submitted for defence are cited.

Chapter One is a general introduction and describing the main problems induced by swift heavy ions effects on surfaces of various materials. The goal of the first chapter is to formulate the problems of interaction of heavy charge particles with solids and the changes of the observed its surface structure. Namely, at first chapter are described: a) The main effects in solids induced by the passage of swift heavy ions with high and super high inelastic energy loss.
b) Elastic and inelastic sputtering and other phenomena on the surface of various materials under irradiation by low and high energy heavy ions.

Chapter Two is devoted to thermal effects caused by passage and implantation of swift heavy ions into solids. The effects of high value energy losses of swift ions and its influence on temperature in a volume around ion trajectory were described on the bases of the thermal spike model. The system of equations for electronic and lattice temperatures in three dimensional case was presented. This system of equations in three dimensional case can be expressed in the form:

$$C_e(T_e)\cdot\frac{\partial T_e}{\partial t}=\frac{1}{r}\cdot\frac{\partial\left(r\chi_e(T_e)\cdot\frac{\partial T_e}{\partial r}\right)}{\partial r}+\frac{\partial\left(\chi_e(T_e)\cdot\frac{\partial T_e}{\partial z}\right)}{\partial z}-g(T_e-T)+A(r,z,t), \qquad (2.1)$$

$$C(T)\cdot\frac{\partial T}{\partial t}=\frac{1}{r}\cdot\frac{\partial\left[r\cdot\chi^{\mathrm{II}}(T)\cdot\frac{\partial T}{\partial r}\right]}{\partial r}+\frac{\partial\left[\chi^{\perp}(T)\cdot\frac{\partial T}{\partial z}\right]}{\partial z}+g(T_e-T). \qquad (2.2)$$

Here, the axis z is directed perpendicular to the target surface, i.e. is parallel to the direction of heavy ion movement; the angular derivative is zero due to cylindrical symmetry; $T_e(r,z,t)$ and $T(r,z,t)$ – electron and lattice temperatures, respectively; $C_e(T_e)$, $C(T)$ and $\chi_e(T_e)$, $\chi^{\|}(T)$ and $\chi^{\perp}(T)$ – specific heat capacity and heat conductivity of electrons and lattice, respectively, as a general rule of temperature dependency the symbols "||" and "⊥" means that the heat conductivity in the lattice subsystem depends on the crystallographic orientation: along the irradiated surface (||) and perpendicular to it (⊥); g – constant of electron-phonon interaction. Generally, the function $A(r, z, t)$ is the volume density of ion energy (power); which transfer to electrons. And this power can be represented as the frequently used expression:

$$A(r,z,t) = b \cdot S_{inel0} \cdot \exp\left[\frac{-(t-t_0)^2}{2\sigma_t^2}\right] \cdot \exp\left(-\frac{r}{r_0}\right) \cdot \mu(z) \qquad (2.3)$$

Here the function $\mu(z)$ – the profile of ion ionization loss as the Bethe-Bloch function (at $\frac{E}{A}$ > 0.25 MeV/a.m.u) or Lindhard-Firsov function (at $\frac{E}{A} \leq$ 0.25 MeV/a.m.u.) normalized to the value of ionization loss upon the entrance in target at z=0:

$$\mu(z) \equiv \frac{S_{inel}(z)}{S_{inel0}}, \quad S_{inel0} \equiv S_{inel}(z=0) \qquad (2.4)$$

Where E (MeV) is the ion energy, A (a.m.u.) – it's mass. The time for electron equilibrium distribution achieving (i.e. the time of free path for δ-electrons with average energy ε_e), $t_0 \approx (1-5) \times 10^{-15}$ s, the half-width of distribution by t was taken as $\sigma_t = t_0$. The rate of exponential decrease or the space width of highly excited zone $r_0 \leq 2.5$ nm or $r_0 \cong 1$ nm. Normalizing factor b is determined from the condition:

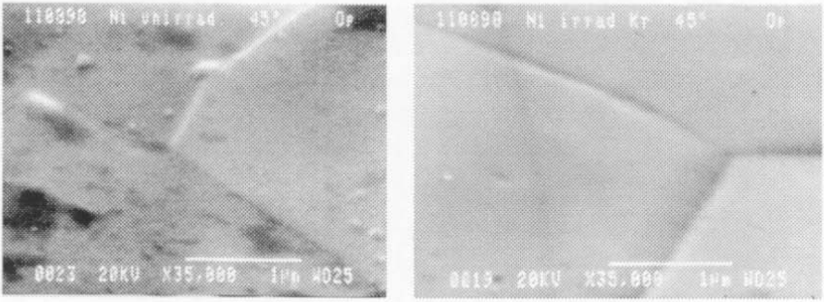
$$\int_0^\infty dt \cdot \int_0^{r_m} 2\pi r \cdot A(r,z,t) \cdot dr = S_{inel} \equiv -\left(\frac{\partial E}{\partial z}\right)_{inel}(z) \qquad (2.5)$$

Where r_m – maximum δ-electron projective range depending on the maximum energy ε_m, transmitted to individual electron. This system of equations without dependence from Z coordinate was first introduced by E. M. Lifshitz in 1950s. The numerical method of the calculations of such differential equations is presented too. The numerical analysis with the use of approximation expressions for the lattice temperature is also given.

The model of thermal spike in solids due to heavy ions irradiation with highly specific inelastic energy losses is studied taking into account the temperature gradient across the trajectory of ion. In the given temperature model, the numerical solution of systems of equation for lattice and electron temperatures taking into consideration the possible lattice heating up to the melting point and evaporation, i.e. a two phase transformations. In addition the application of pressure in the track, and its effect on the variation of thermodynamical parameters of the lattice are studied. The numerical analysis using approximation expressions for the lattice temperature were also presented.

Chapter Three describes the ion facility for irradiation of samples; the accelerator U-400 at FLNR. The results on the sputtering of pure metals Ni, W, Au and stainless steel Cr18Ni10 by swift heavy ions in the inelastic energy loss regime were presented.

The presence of radiation defects in metals essentially amplifies the influence of inelastic energy loss of fast heavy ions as shown that in this case the sputtering coefficients increase significantly. The sputtering coefficients for metals having only small concentration of defects is about 1-10 atom/ion. However, the sputtering coefficient for coarse-grained metals under swift heavy ion irradiation increased by factor 3 times of order at high irradiation fluences (~2×10^{15} ion/cm^2), because the effect of radiation-induced defects accumulation in the crystal during the ongoing irradiation of the target. The experimentally observed high sputtering coefficient for nickel can be explained by atom evaporation from the ion track surface which has been heated up to boiling temperature T_b, i.e. the thermal spike model (Chapter 2), can work at high concentration of damage and initial defects. In this way we experimentally proved that inelastic energy loss $(dE/dx)_{inel}$ of swift heavy ion has a strong influence on the sputtering of metal with a high defect levels in the crystalline structure. The observations show strong heterogeneity of the metal surface sputtered with swift heavy ion irradiation. The presented results were explained by track formation and consequently the high evaporation leading to high sputtering coefficients in case of solids with high concentration of defects of all types (point defects, cluster of defects, longitudinal-extended defects and grain boundaries). The scanning electron microscopy (SEM) images for Ni which is presented in Fig.1, showed the surfaces after irradiation with 305 MeV ^{86}Kr ions up to fluence $F{\cdot}t=2 \times 10^{15}$ ion/cm^2. One can observe that the metal surfaces were polished by irradiation, and surface irregularities were sputtered. Furthermore, from Fig.1 it is possible to see a considerable material sputtering near the grain boundaries. The sputtering coefficient at the grain boundary S is ≈ 2000 ± 500 atom/ion.



A *B*

Fig.1. SEM Micrographs of the surface structure of polycrystalline Ni before (*A*) and after irradiation (*B*) with 305 MeV ^{86}Kr ions up to fluence $F{\cdot}t=2\times10^{15}$ ion/cm^2.

In the case of polycrystalline Ni previously irradiated with high fluence the *step* method was used to have an approximate estimation of sputtering coefficient as depicted in Fig.2.

Scanning tunneling microscope (STM) allows more accurate determinates of the sputtering coefficient due to high energy ion irradiation. The mean surface relief height values for unirradiated (*A*) and irradiated (*B*) samples, as estimated from the scans such as depicted in Fig.3 is high: 53.97 nm and 11.66 nm, respectively. We calculated the mean height values using many scans for unirradiated (*A*) and irradiated (*B*) areas.

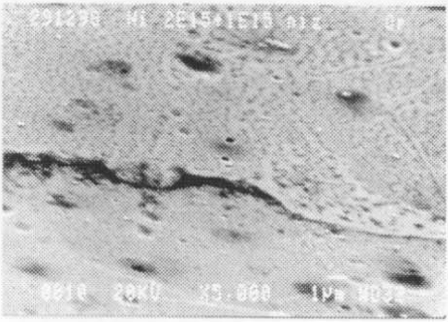


Fig.2. The surface structure of Ni previously irradiated with 305 MeV ^{86}Kr ions up to the fluence $F{\cdot}t = 2\times10^{15}$ ion/cm^2 (upper half of image) and then irradiated with 245 MeV ^{86}Kr ions up to the total fluence of $F{\cdot}t = (2\times10^{15}+1\times10^{15})$ ion/cm^2 (lower part of image). The upper part was covered by a mask when the sample was irradiated. A step of average height $h \sim 0.3$ μm is formed between the two parts.

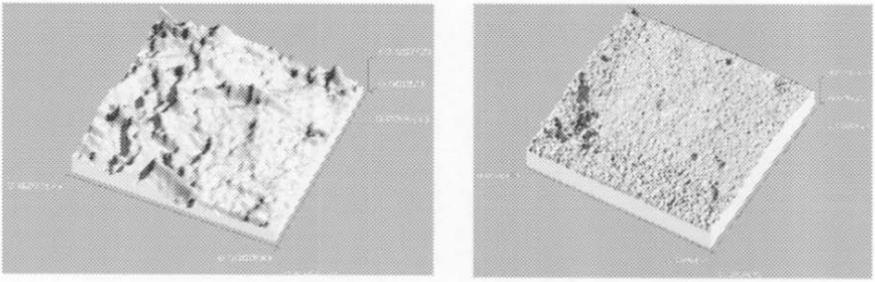
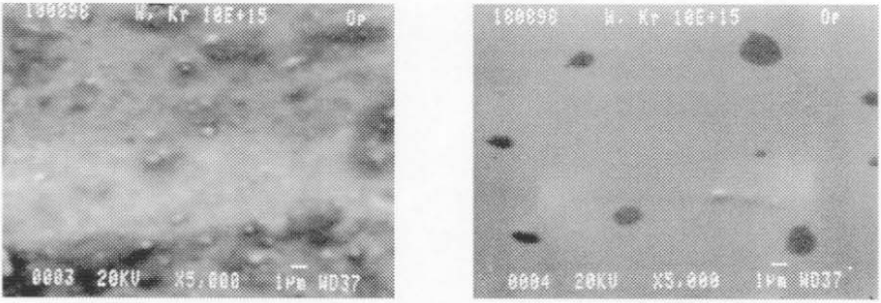

A *B*

Fig.3. The nickel surface structures in initial sample (*A*) the scanned area is 2.6 μm ×2.6 μm and height is 54 nm and after irradiation with 305 MeV Kr ions up to fluence $F{\cdot}t = 2\times10^{15}$ ion/cm^2 (*B*) the scanned area is 3.15 μm × 3.15 μm and height is 47 nm. The images were obtained by means of STM technique

The investigation of the sputtering coefficient for W single crystal and stainless steel Cr18Ni10 (SS) was carried out for comparison. In addition, the post-irradiation chemical element composition of irradiated SS was determined. The surface structures of tungsten single crystal before (*A*) and after (*B*) irradiation with

305 MeV ^{86}Kr ion up to fluence $F{\cdot}t=2\times10^{15}$ ion/cm^2 are presented in Fig.4. The images were obtained by scanning electron microscopy.

The interesting observation of hillock-like features formed on the surface of irradiated stainless steel is also a necessary step to understand results as that presented in and discussed in the introduction. As these results might stem from temperature effects in the area around the ion trajectories. Our observation of the surface stainless steel is very similar to observed features due the phenomenon of blistering.



A *B*

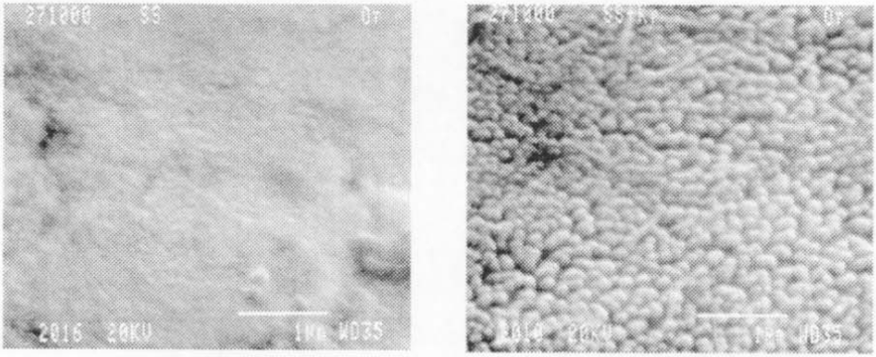
Fig.4. The surface structures of single tungsten crystal before (*A*) and after (*B*) irradiation with 305 MeV ^{86}Kr ions up to the fluence $F{\cdot}t=2\times10^{15}$ ion/cm^2.

The surface structure of chromium-nickel stainless steel (Cr18Ni10) irradiated with ^{86}Kr ions is presented in Fig.5. showing the SS surface structures in initial state (Fig 5*A*) and after irradiation with fluence up to $F{\cdot}t=2\times10^{15}$ ion/cm^2, (Fig 5*B*). As one can see, the irradiated chemically mulicomponent surface exhibits the interesting structure of the hillock-like features.

Electron microprobe analysis for the SS samples irradiated with 245 MeV ^{86}Kr ion up to fluence $F{\cdot}t=5\times10^{15}$ ion/cm^2 was carried out in the electron scanning microscope JSM-840. It was found that Ni content becomes about half as much after irradiation. The chemical composition of SS sample changes from $Fe_{69.7}Cr_{17.6}Ni_{12.7}$ to $Fe_{73.7}Cr_{19.7}Ni_{6.6}$.

Besides that the results of measurements of sputtering coefficients of cold-deformed gold irradiated by ^{86}Kr ions with energy 253 MeV up to fluence 10^{14} ion/cm^2 are presented. It was shown that cold-deformed gold with high density of dislocations has the sputtering coefficients much grater the good annealed course grain gold samples.

On the base of data obtained for Ni, W, chromium-nickel steel we concluded that the thermal spike model can be invoked to describe the observations as the high temperatures can reach the evaporation temperatures leading to strong sputtering process, especially at grain boundaries.



A *B*

Fig.5 SEM micrographs of stainless steel surface in the initial state (*A*) and after irradiation with 245 MeV ^{86}Kr ions up to fluence $F{\cdot}t=2\times10^{15}$ ion/cm^2 (*B*).

Chapter Four presents the results on the High Oriented Pyrolytic Graphite (HOPG) irradiated by swift heavy ions ^{209}Bi and ^{86}Kr. The STM image of HOPG surface before (*A*) and after irradiation (*B*) with 305 MeV ^{86}Kr ions at the fluence of 5×10^{12} ion/cm^2 is presented in Fig.6. Part of the sample surface was covered by a special mask and thus was unirradiated, while the other part was exposed to ions. The grain boundaries were studied in detail using the STM technique. For the unirradiated part of the HOPG sample, one can observe a boundary between two crystal grains, while on the irradiated part one can see a strongly sputtered (eroded) boundary. The boundary depth in Fig.6*A* is estimated to be 5 Å, while in Fig.6*B* it is equal to 47 Å. Therefore, the boundary sputtering predominates over sputtering inside the grain.

The STM image of HOPG irradiated with ^{209}Bi ions at fluence 10^{12} ion/cm^2 with energy 705 MeV is presented in Fig.7. One can see the craters which were formed on the surface of individual HOPG grain after ^{209}Bi ion irradiation. The analysis of all STM images has shown that the mean surface crater density is only about 2-3% of the total ion fluence (10^{12} ion/cm^2).

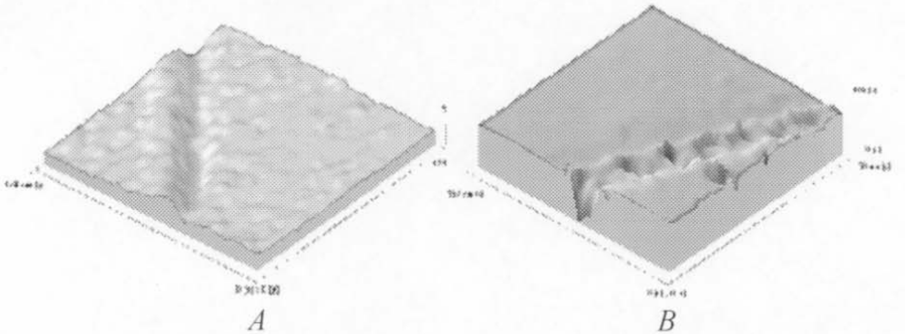


Fig.6. STM-images of initial (*a*) and irradiated with 305 MeV ^{86}Kr ions up to fluence 5×10^{12} ion/cm^2 (*b*) HOPG surfaces. The scanning areas are 128 nm × 128 nm *(A)* and 167 nm × 160 nm *(B)* and the depths at grain boundaries are 5 Å (*A*) and 47 Å (*B*).

A cylindrical region of excited electrons will be formed around the trajectory of high energy ion in solid targets. The radius of this region is r_0~10 Å and initial electron gas temperature is about 20-40 eV. The subsequent relaxation process of the excited electrons will take place due to electron-electron collisions (electron thermal conductivity) and electron-lattice interactions, which leads to lattice atom heating. In the HOPG case the excited electron region cooling based on electron thermal conductivity will be strongly straitened because the free electron density for single crystal graphite is three orders of magnitude less than that in metals and has a value $n_e \approx 5\times10^{18}$ electron/cm^3. Thus, a significant part of excited electron energy will be transferred to ionized lattice atoms and this phenomenon takes place in a cylindrical excited electron region.

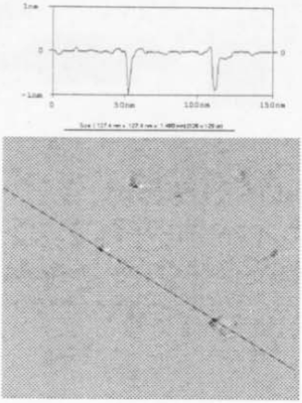
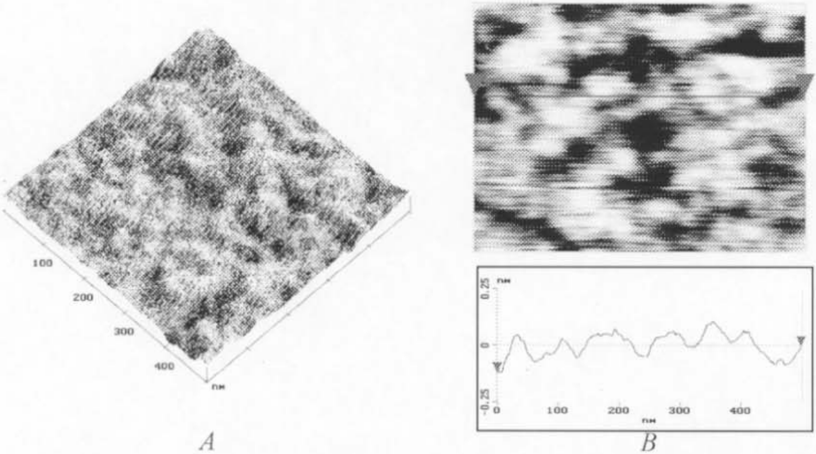


Fig.7. STM-image of the HOPG surface structure irradiated with 705 MeV ^{209}Bi ions up to the fluence of 10^{12} ion/cm^2. On the top figure one can see the scanning profile along the line shown on the bottom figure-scanned area 127 nm × 127 nm.

It is clear that level of inelastic energy loss of ^{86}Kr ions in HOPG not enough (inelastic energy loss of ^{86}Kr ions with energy 305 MeV on the surface of HOPG is equal to $-(dE/dx)_{inel} = 12$ keV/nm) to cause any changes of surface structure of individual crystalline, but the sputtering of grain boundaries happens (Fig.6) due to high level of structure defects, As in the case of metals (see chapter III). The level of inelastic energy loss of ^{209}Bi ions (inelastic energy loss of ^{209}Bi ions with energy 705 MeV on the surface of HOPG is equal to $-(dE/dx)_{inel} = 27.6$ keV/nm) practically comparable (enough) with threshold sputtering energy for sputtering of crystalline surface. But the sputtering of crystalline surface takes place the thermo-fluctuation character.

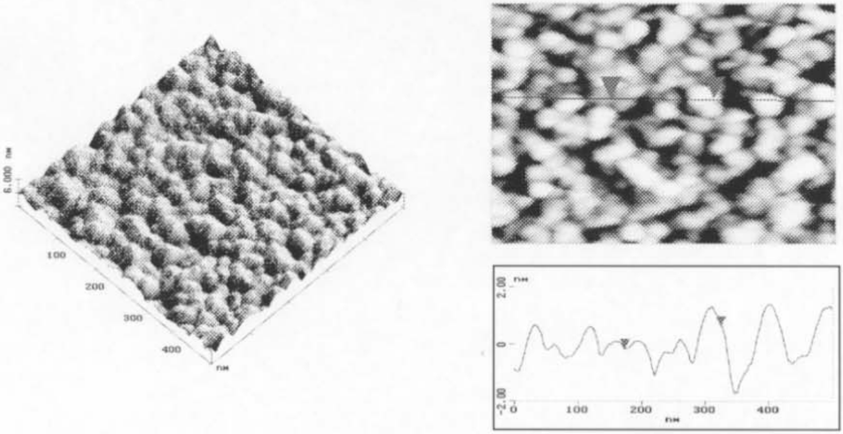
Chapter Five presents the results on the experimental investigation of single crystalline Si irradiated by 253 MeV ^{86}Kr ions. The fluences of irradiation were 10^{14} and 2.6×10^{15} ion/cm^2. The surface changes of single crystalline silicon irradiated by swift ^{86}Kr ions were studied using the Atomic Force Microscope (AFM). In Fig.8.*A* a three dimensional image of the initial surface and corresponding scanning profile along a line across the sample - Fig.8.*B* one can observe that inhomogeneity of initial surface less then ±0.1 nm indicating the excellent surface quality and smoothness of the crystal. The AFM image of irradiated silicon surface (253 MeV ^{86}Kr ions, fluence of 2.6 $\times 10^{15}$ ion/cm^2) is presented in Fig.9*A* The scanning profile along the surface of irradiated Si surface is presented in Fig.9.*B*. The level of relief in irradiated surface is less than ±2.0 nm i.e. the irradiated surface became rough in comparison with the initial smooth unirradiated surface (see the Fig.8*B*). The estimations of inelastic sputtering of Si were carried out.



A *B*

Fig 8. Three dimensional AFM image of unirradiated surface of single crystalline Si (A) and a line scan across the surface (B).

In conclusion main results of thesis are presented. Also synopsis of the basic results of the thesis submitted for defense is presented. The results of heavy ion irradiation in the inelastic energy loss region on the structure of some metals. It was shown that sputtering coefficient (yield) strongly depends on the state of the irradiated surface and the density of defects in the crystalline target, whether it is present before the irradiation (point defects, extended defects, etc.) or as a result of accumulation and build up of defects due to irradiation. The presence of these defects essentially increases the influence of inelastic energy losses of the high energy heavy ion and hence the sputtering coefficients. Strong inhomogeneity of the sputtering of surfaces by high energy heavy ions is thus expected. It was shown on the samples of stainless steel and Si, irradiated by swift heavy ions very clear. The sputtering at the grain boundaries are much greater than surfaces of grains itself.



A *B*

Fig.9. A three dimensional AFM image of the surface of irradiated Si by ^{86}Kr ions with energy 253 MeV, the fluence was 2.6×10^{15} ions/cm^2 (A) and the profile along the indicated scanning line (B).

The importance of the sputtering problem in the fields of nuclear engineering, high-energy heavy ion implantation and processing of novel materials makes it necessary to continue the efforts of similar experimental and theoretical studies on swift heavy ion irradiation to elucidate the various aspects of the phenomenon.

The main results of the thesis were published in the following articles:

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Received on November 21, 2005.

Отпечатано методом прямого репродуцирования
с оригинала, предоставленного автором.

Подписано в печать 24.11.2005.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 1,37. Уч.-изд. л. 1,42. Тираж 100 экз. Заказ № 55119.

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