FACILITY FOR STUDY OF RADIATION RESISTANCE REACTOR MATERIALS ON BEAMS OF ACCELERATED METAL IONS

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ABSTRACT
Requirements safe operation of nuclear facilities dictate the necessity of regular study of radiation damage of materials used in nuclear reactor industry. The experimental tests of structural materials in atomic reactors are very expensive and they take long time. The irradiation of these materials by charge fast particle beams on accelerates allow to get such experimental data for physical mechanisms of radiation resistance of them more easy during short time without high radioactivity level on irradiated samples. Such operations are conducted at the Institute of Applied Physics of NAS of Ukraine (IAP NAS of Ukraine). Installation for simulation studies on metal ion beams (Fe, Ni, Cr, Cu, Zr, Mo, etc.) with energies of 20÷500 keV was designed. Gas magnetron metal ion source of sputter type was used. Computer simulation of processes of ion beam extraction from plasma boundary of the ion source and beam transporting in the ion-optic system of the implanter was made. Mass-spectra of ion beams were obtained.

KEYWORDS
Reactor materials, metal ions, ion beams, irradiation, ion implanter, computer simulation.

1. INTRODUCTION
In recent decades works on modification of materials with high-energy ion beams (ion implantation) are intensively developing. Field of application of ion implantation is very various: microelectronics, space and nuclear instrumentation, processing of tools and details of machines for the purpose of change of their physical and chemical properties, etc. [1–3].

One of the possible areas of application of ion-beam processing is research of radiation firmness of constructional materials used in nuclear energetic [4, 5]. The accelerated heavy ions have on some orders greater values of cross-sections of interaction with atoms of a crystal lattice, than reactor neutrons. Therefore use of heavy ions, especially ions of metals, allows creating in some hours in materials radiation defects which in the most powerful nuclear reactors are reached for many years [6]. Also test samples practically have no induced radioactivity, and there is a possibility of control and change of the sample temperature and ion beam intensity in a wide range.

Besides, ion radiation has two essential advantages against the neutron one. First, for radiation swelling research it is important to carry out irradiation of metals with ions of the same sort as of atoms of an irradiated target. The second advantage is a possibility of implantation in a test material of practically any elements. This opens wide prospects for modeling of various defects caused by emergence of chemical in
homogeneities in materials. In this regard, the interest to physics of heavy (metal) ions that demands development of the corresponding experimental equipment for surface modification has considerably grown in recent years.

EXPERIMENTAL INSTALLATION

In IAP NAS of Ukraine works on construction of the installation for high-dose and high-energy implantation of metal ions are being conducted. Implanter is based on vacuum system and high-voltage supply of the industrial ion implanter “Vezuviy-5” [7]. Installation in the implanter of the metal ion source developed by us allows to carry out precision irradiation of samples in the sample chamber with metal ions (Fe, Ni, Cr, Cu, Zr, Mo, etc.) and gas ions (H, He, N, O, Ar, etc.) in a range of energies from 20 to 500 keV. The current in the sample chamber approaches 10 ÷ 50 µA for metal ions and 200÷300 µA for gas ions. The general scheme of experimental installation is presented on Fig. 1.

![Figure 1. Installation for modification of materials with metal ions (top view)](image)

The beam of metal ions is generated and formed in ion injector 1. The inflow of ballast gas in the source is done by means of a mechanical needle valve with a stepping motor. As the ion source creates considerable gas load on vacuum system of installation, differential pumping of the ion source was realized by means of turbomolecular pump being underground potential and connected to the ion source through insulating polyamide pipe. The energy of single charged ions at the ion source exit can be set in the range of 5…20 keV.

Mass separation of ions is carried out in 900 sector electromagnet 2 with the maximum mass number.
M/Z \sim 60. After separation ions are focused again by an einzel lens 3 and accelerated to needed energy in an accelerating tube 4. The ion source, electromagnet, einzel lens and their power supply modules are under high positive potential (up to 150 keV). Cooling of the ion source and electromagnet is carried out by supply of distilled water through a plastic tube reeled up on a bakelite cylinder.

The accelerated beam gets to the first reception chamber 5 being under ground potential. For cutting off a neutral component of the ion beam the plates 6 deflecting the accelerated beam in the horizontal plane on a small angle are mounted at the entrance of the chamber. The deflected ion beam gets to the system of horizontal and vertical scanning 7 (the scanning area varies from 10×10 mm² to 100×100 mm²). Immobile 8 and mobile 9 Faraday cups for measurement of ion beam current are mounted in the first chamber. Electrostatic lenses inside the ion injector and at the mass separator exit, and the beam scanning system allow to regulate ion current density in the test sample plane in a wide range (10² ÷ 100 µA/cm²).

Further the beam gets to the second chamber 10 connected with first one through the high-vacuum valve 11. Another accelerating tube 14 with the holder of irradiated samples 15 at the end is mounted in the second chamber. This chamber is under high negative potential (up to -100 keV), supplied by high-voltage source IVN-100. Thus, the energy of ions bombarding a sample reaches 250 keV for single charged ions and 500 keV for double charged ions. Electrodes of the accelerating tube and the sample holder are connected through a voltage divider in such a way that between the holder and the last electrode of the tube there exists a potential drop (1 ÷ 2 keV) that locks emission of secondary electrons from a sample.

The temperature of irradiated samples can be regulated in a range of 100 ÷ 600 °C by means of the heater 18 based on a halogen lamp with a water cooled reflector. Measurement of sample temperature is conducted by means of a thermocouple and a voltmeter fixed on the sample holder (Fig. 2).

![Figure 2. Photo of the reception chamber number 2](image)

The dose of radiation is measured by the system of Faraday cups 12 and ion current integrator. The carousel 13 for mounting of irradiated samples is used in this design for masking and overlapping of an ion beam. Pumping of the both chambers is carried out by diffusion pumps 16, 17 with the traps cooled with liquid nitrogen. The residual gas pressure in the chambers is 2·10⁻⁴ Pa.

**ION SOURCE**
The metal ion source developed in IAP NAS of Ukraine allows generating beams of single and double charged ions of metals on the basis of ion-plasma sputtering [8]. Such a way of creating of a working environment allows forming atomic concentration practically of any metals without a need of heating up a source to high temperatures. The design of the source is schematically shown on Fig. 3.

![Figure 3. The scheme of metal ion source](image)

The physical basis of principle of action of the source are two sequential discharges – modernized magnetron $M$ and classical Penning $P$ which divide the gas-discharge chamber of the source into two sequential zones.

Preparatory processes are realized in the magnetron discharge:

– effective generation of argon plasma in the crossed electric and magnetic fields;
– enrichment of this plasma at the exit of the magnetron with metal atoms generated from a sputtered near-cathode insert;
– drawing of the plasma of the gas-vapour environment to the entrance of the Penning discharge.

The chain of elementary processes ends in the Penning discharge:

– increase of partial pressure of metal atoms at the expense of sputtering of the anti-cathode insert and localization of metal atoms in emission area;
– ionization of atoms close to axis of emission area by abnormally fast electrons oscillating on an axis of the Penning discharge.
Argon is the ballast gas supplied to the ion source. Inverse gas magnetron consists of the cold cathode made of molybdenum or graphite, and the shortened copper anode. The discharge current is about 3 A and the voltage drop is 400 V. Plasma generated in the magnetron acts as cathode of the Penning discharge, the anti-cathode is the electrode, and the anode is the thermally isolated molybdenum electrode. The anti-cathode carries out function of an emission electrode of the extraction system. Sputtered inserts are located at the exit of the magnetron and in the axial area of the anti-cathode (marked with solid filling).

The magnetic system of the source includes permanent magnets and magnetic circuit (marked with STEEL shading). The main magnets generating magnetic field (~ 0.1 T) in the gas-discharge chamber of the source, are mounted in the back part of the source. Correcting magnets with radial magnetization and an additional magnetic pole increase magnetic field in the Penning discharge cell to 0.2 T. This provides the increased concentration of plasma in the extraction area. The specific feature of the Penning discharge is existence on its axis of abnormally fast oscillating electrons.

In formation by sputtering of a working environment in the discharge chamber one can distinguish two main ways of losses of metal atoms. First of all, as a result of the fact that the metal atom loss rate due to diffusion from the discharge considerably exceeds the rate of ionization of metal ions by electron impact. Secondly, as a result of vapour condensation on the cold surrounding surface. In the ion source the first way of losses is minimized by effective ionization of atoms with fast oscillating electrons in the atom sputtering area. Vapour condensation is prevented by the fact that the thermally isolated Penning anode has working temperature of about 1600 °C.

Histograms of current distribution of beam fractions with respect to the total beam current are presented on Fig. 4 (obtained on the ion source test stand in the pulse operating mode, h.f. is a total current of heavy ion fractions M/Z > 100).

Figure 4. Mass composition of the beam during iron (a) and zirconium (b) sputtering

The design of the ion source allows working with magnetic and non-magnetic sputtered materials. Optimization of the source for receiving multicharged metal ions with Z = 2; 3 is possible. Photos of the ion injector are shown on Fig. 5.
Figure 5. Photos of the ion injector itself (a) and as a part of experimental installation (b)

COMPUTER SIMULATION

For definition of optimum geometry and potentials of ion-optical system elements of the installation computer simulation of heavy ion beam transportation process was carried out. This simulation includes two stages:
– finding of a plasma boundary (meniscus) shape in the source of metal ions, influencing beam divergence at the exit of the source;
– simulation of beam passing in the subsequent elements of ion tract of the installation.

For simulation of formation process of plasma boundary in the ion source with axial symmetry the corresponding software Plasma2D was developed. The program was created in the Delphi 7 environment and occupies memory about 1 Mb [9]. Its block diagram is shown on Fig. 6.

Figure 6. The general algorithm of the program for simulation of ion beam extraction from plasma

Calculation of electric field $U$ in the considered area is made by the numerical solution of Poisson equation in cylindrical coordinates $(r, \varphi, z)$ taking into account axial symmetry of potential distribution

$$
\frac{\partial^2 U}{\partial r^2} + \frac{1}{r} \frac{\partial U}{\partial r} + \frac{\partial^2 U}{\partial z^2} = -\frac{\rho}{\epsilon_0},
$$

(1)
where $\rho$ is a space charge density, $\varepsilon_0$ is an electric constant. The solution is found by the method of iterations on the finite difference scheme under the preset boundary conditions and grid step.

The definition of specific geometry of ion extraction system and the initial position of the plasma boundary is made by loading in the program of the raster image (in the .gif format), previously created by the user in a graphic editor and representing the section passing through the axis of system. It is accepted that white pixels correspond to vacuum, black – to electrodes, and red – to the plasma meniscus. After that, the user sets potentials of electrodes and plasma, and the program assigns the entered potential value to the corresponding grid nodes. Each pixel of the image has corresponding grid node.

Drawing of particle trajectories in the calculated electric field is made by numerical integration of the differential equation of movement under the preset start conditions (coordinates, energies and flight angles of particles). For accuracy increase the integration step changes in time according to particle velocity and acceleration.

Then the self-consistent problem is solved with plasma boundary shift at each stage according to electric field intensity $E$ on plasma surface. For smoothing of the plasma shape received as a result of shift, the surface is approximated by a polynom of $N$ degree set by the user. The criterion of computation process completion is the root-mean-square deviation of potentials of grid nodes adjoining to plasma boundary from the plasma potential which should not exceed the value set by the user.

One more possibility of the program is drawing of a beam phase portrait and calculation of emittance at a certain distance from the plasma boundary. During the simulation process optimum potentials of elements of ion beam extraction system at which beam divergence at the injector exit is minimal were defined (Fig. 7,a).

![Diagram](image)

**Figure 7. Results of computer simulation of 56Fe+ ion extraction from the plasma boundary of the source: a – Plasma2D, b – IBSIMU v.1.0.5**

Potential of emitter (pos. 1) was 12 kV, of extractor (pos. 2) -20 kV, of focusing electrode (pos. 3) 10 kV at the current of Fe$^+$ ion beam of 1.5 mA. Diameter of aperture was 1.5 mm in the emitter and 3 mm in the extractor, a gap between the emitter and the extractor was 5 mm, and the grid step was chosen to 0.03 mm.

For validation of the obtained results one more simulation with the use of free library IBSIMU v.1.0.5
[10] was carried out at the same parameters and extraction geometry (Fig. 7,b). According to the result of simulation a good compliance of beam particle trajectories is observed. The plasma boundary shape in both cases is close to flat.

Then, computer simulation of Fe ion beam transporting in ion-optical system of the implanter up to beam scanning system was carried out (Fig. 8). The optimum parameters of the injector received earlier were used. The accelerating tube, as shown in figure, forms a beam crossover in the scanning system area. The einzel lens disposed before the accelerating tube allows stabilizing the crossover position when changing accelerating tube voltage.

![Figure 8. Result of computer simulation of iron ion beam transporting in the ion-optical system of the implanter](image)

On Fig. 9 the histogram of ion current distribution of separate fractions of the beam measured by Faraday cup in the first chamber is presented.

![Figure 9. Ion current distribution of the beam fractions at iron sputtering](image)
Parameters of the ion-optical system of the implanter corresponded to Fig. 8. The current of double-charged iron ions was about 25% of that for single-charged ones. In the beam generated by the source, there can also be heavy ions with \( M > 100 \) (for example, \( \text{Fe}^{2+} \) and \( \text{Fe}^{3+} \) clusters) which cannot be registered because of a limited mass range of the mass separator.

Calculations show that radiation damage rate at irradiation of samples by iron ions with energy to 500 keV is in a range of \( 0.1 \div 0.01 \) dpa/s.

**CONCLUSIONS**

For the purpose of radiation material science research the installation for irradiation of materials with metal/gas ions (\( \text{Fe}, \text{Ni}, \text{Cr}, \text{Cu}, \text{Zr}, \text{Mo}, \text{etc.} \)) was created in IAP NAS of Ukraine. Optimization of the ion source operating mode allows receiving the raised percentage of double-charged ions and, thus, increasing in 2 times their maximum energy. The carried-out computer simulation and optimization of ion-optical tract of the installation gives the possibility of regulating the position of ion beam crossover at change of the accelerated ion sort and energy. It allows keeping constant the ion beam size on a target at change of ion energy in a range of \( 20 \div 500 \) keV. Ion beam parameters provide radiation damage rate at level of \( 0.1 \div 0.01 \) dpa/s. The temperature of irradiated samples is regulated in a range of \( 100 \div 600^{\circ} \text{C} \).

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**REFERENCES**


