THE USE OF HEAVY ION CYCLOTRONS OF THE FLEROV LABORATORY OF NUCLEAR REACTIONS IN CONDENSED MATTER INVESTIGATIONS

R.Ts. Oganessian, A.Yu Didyk
Flerov Laboratory of Nuclear Reaction, Joint Institute of Nuclear Research, Head Post Office, P.O. Box 79, Moscow, 101000 Russia

ABSTRACT

The goal of the present work is the presentation of separate reseach directions in radiation physics of condensed media and the results obtained while carrying out these works at present at FLNR.

1. INTRODUCTION

With the development of accelerating technique and as a result the emergence of power radiation sources, one of the reseach directions besides the intensive growth of nuclear and atomic physics is radiation solid state physics (of condensed metter). This direction is rapidly grown in a member of leading centres of the developed contries.

The creation of heavy ion accelerators with high intensities of ion beam (F) and energies (E) exceeding $1MeV/a.m.u.$ essentially expands the leading investigations both for the development of general concepts of radiation damage physics and for the materials modification for the purpose of radiative-stimulated change of their properties and new technologies creation in semiconductor technique.

2. EXPERIMENTAL PROCEDURE AND RESULTS

2.1. IRRADIATION CONDITIONS

Samples irradiation of different materials is realized on U-400, U-200 and U-100 heavy ion accelerators FLNR both in vacuum and on ion beams extracted into the air or atmosphere of other gases (e.g.inert gases).

Irradiation temperature can be varied from the temperature of liquid nitrogen (T=77K) up to 1000°C depending on required irradiation conditions. Ion flux density (F) is varied from 10^2 up to 10^{12} ion $/cm^2s$. The irradiation is carried out by ions from He to Xe with energies from $1MeV/a.m.u.$ up to $10MeV/a.m.u.$

If it is necessary ion beam can move on the plane of irradiation along horizontal by 15 cm and along vertical by 5 cm towards both sides from ionowire axis that allows the uniformily of irradiated square $30 \times 10cm^2$ to be not worth than 5%. The studing of peculiarities of the point defects accumulation in samples irradiated by heavy ions is realized by different nuclear physical and other methods. Such methods are: electron scanning and transmission microscopy, x-ray structural analysis, methods of positron-electron annihilation (by positron lifetime and angular correlation of annihilation γ -quanta), methodics of measurements of samples electroresistance, methodics of determination of mechanical properties changes (methods of microhadness and measurement of yield point and other characteristics by means of tensile testing machines of the "INSTRON" type), methods of photo-, cathode- and ionolumenescence, methods by spectra of light absorption and etc.

2.2. INVESTIGATION OF RADIATION EFFECTS IN METALS AND ALLOYS

One of the most important effects by neutron irradiation in reactors resulted in their structural materials is swelling and radiation hardening. In the work[1)] there was studied radiation copper swelling by irradiation of inert gas ions Xe and Cu ions with the energies of $1MeV/a.m.u.$. There were obtain dose and temperature dependensies of swelling value and shown that by ions Xe irradiation there is an anomalous temperature shift of swelling maximum in comparison with Cu ions irradiation which can be explained by different behaviour of implanted ion interaction with vacancy complexes.

The cycle of works on studying of radiation hardness of a number of pure metals (Al,V,Ni,Cu,Zr),[2-4,6)] radiation annealing hardness of vanadium alloys series with Al, Fe, Nb, Ti, Y[5)] and also stainless steel Cr18Ni10Ti and etc. In Fig.1 there is shown the change of Cr18Ni10Ti steel microhardness from fluence for three ions: B (13 MeV), Ne (27 MeV) and Ar (46 MeV)- curves 1,2 and 3 respectively (annealed samples with low dislocation density), and also B and Ar- curves 4,5 respectively (cold-deformed samples with high dislocation density).

As seen, in all cases one observes the saturation of radiation hardness with fluence. Saturation level value depends on mass of irradiating ion, it increases together with ion mass increasing. This is connected with the differencies in defect structure, produced by ions of different masses. The degree of hardness is higher for cold-deformed samples in comparison with annealed ones.

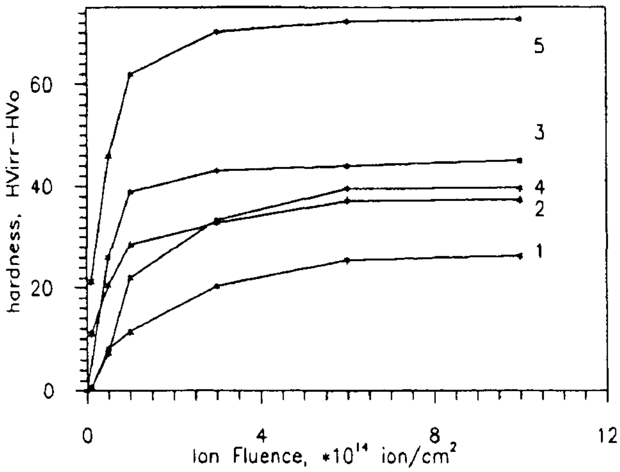

Fig. 1. Fig.1. The hardness of Cr18Ni10Ti stell versus ions fluence.

By anology of effects of radiation influence from neutron and heavy ion irradiation there was studied the effect of radiation annealing hardness of a number of vanadium alloys.

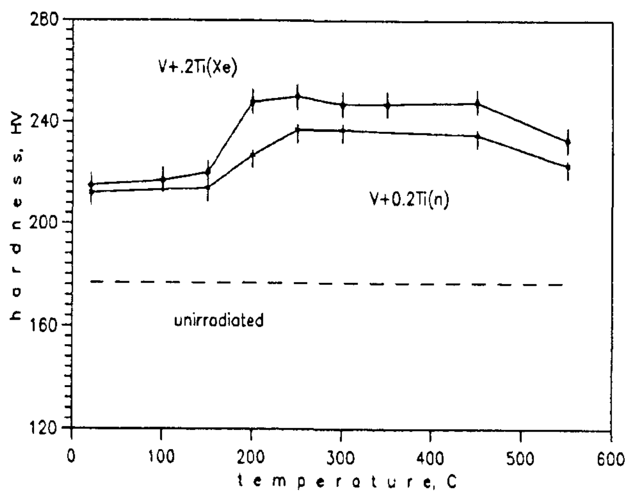

Fig.2. The change of V+0,2%Ti alloy microhardnes versus temperature of post-radiation annealing.

In Fig.2 the change of V+0,2%Ti alloy microhardness from temperature of post-radiation annealing is shown. The curve 1 is irradiation by Xe ions with the energy of 124 MeV ($D = 6,5 \times 10^{-3} dpa$), curve 2 - irradiation by fast neutrons ($D = 9 \times 10^{-4} dpa$). It is seen, that maximum radiation annealing hardness takes place at temperature $200^o C$, and the behaviour of annealing curve change for ions and neutrons is similar qualitatively. This fast allows to draw a conclusion about the legitimacy of effects simulation of radiation annealing hardness from neutrons by heavy ions.

2.3. PROJECTIVE RANGE OF HIGH ENERGETIC HEAVY IONS ($1-6 MeV/a.m.u.$) IN SEMICONDUCTOR AND DIELECTRIC MARERIALS

Space positions of radiation damage's maximumes resulting from implantations of high energetic ($1 - 6 MeV/a.m.u.$) B, O, Ne, Ar, Kr, Xe, Pb ions into practically used semi conductors were measured with an optical and scanning microscopy techniques. The monocrystals of Si, Ge, GaAs and a model ionic crystal of LiF were used as targets. The experimental data were compared with the same values and projected ranges, calculated with the TRIM-89[7] and E-DEP-1[8] computer programs. High energy ion implantation is mainly used in the case, when the inelastic stopping power determines ion's losses of energy. The adequacy of the description by modern theoretical models of ionization energy's losses in a wide band of energies and atomic numbers was investigated. The ratios of experimental to theoretical ranges is represented in Fig.3 and shown the goodness of the theory for velocities of ions exceeding $v_o Z_1^{2/3}$, where v_o is the Bohr velocity and Z_1 is the ion's atomic number (that is for Bethe-Bloch theory case).

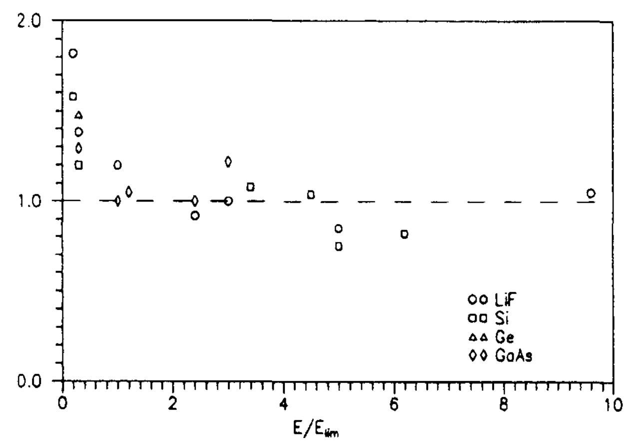

Fig.3.Comparison of experimental and theoretically calculated range's values of ions in different targets (□ - Si, △- Ge, ◇- GaAs, ○- LiF). $\delta = R^{exp}/R_c$ and $E_{lim} = A_2 v_o^2 Z_1^{4/3}$

It was shown, that at the same time the TRIM program gave an essential discrepancy with the experiment, especially for big atomic numbers, when ion's velocity below or equal to that parameter.

2.4. RADIATION EFFECTS IN SEMICONDUCTOR AND DIELECTRIC SINGLE CRYSTALS

The high energy ion implantation into the semiconductor materials, with high energies at $(dE/dx)_{inel}$. $(dE/dx)_{el}$ has a member of essential pocuiliarities in comparison with low-energy one. In connection with high specific ion losses the local region heating-up near projective ion range - "ion track" takes place that causes the enhancement of point defects-i.e. intersticials and vacancies and moreover recrystallization of destruction region even in such high-melting monocrystal as diamond.[9)]

The investigations on production of defects in monocrystals Si, GaAs and a member of others were carried out by the methods of infrared absorption, x-ray structural analyses, secondary masses of ion spectroscopy, measurement of electroresistance etc. In Fig.3 there is the dependence of point defects concentration irradiated by the ions of Ar with the energy of 46 MeV up to fluence $Ft = 7 \times 10^{14} cm^{-2}$ of Si sample on the depth by ions range. The curve is obtained by using the x-ray analysis (from data of measurement of lattice parameters. The curve 1- experiment, and curve 2- the calculated dependence by means of the TRIM-89 program.

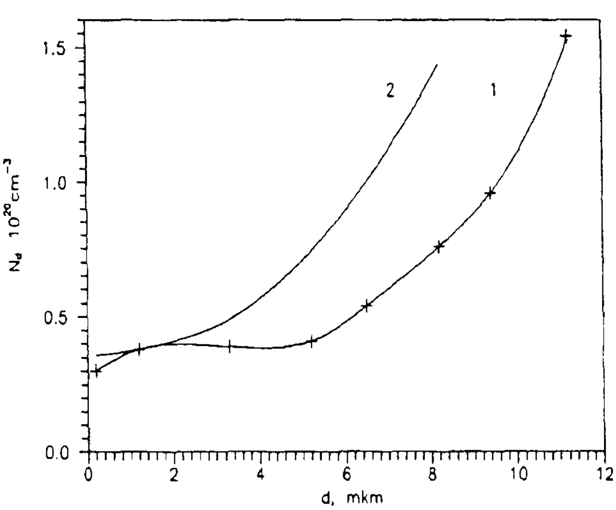

Fig.4. Profile of distribution of defects concentration (1- experimental, 2- calculated) from the depth in monocrystal Si irradiated by the Ar ions.

It is seen that the calculated profile is essentially differs from the measured one, it denotes that while accumulation of point defects there simultaneously occur the intensive processes of their munual annihilation at the same time the more is the contribution of these processes the more is the concentration of point defects.

In Fig.5 the dependencies of the relative reflection coefficient of the light with wavelength $\lambda = 650nm$ - $k = \Delta R/R\%$ for Si irradiated by B (E=14 MeV, $Ft = 8 \times 10^{14}$ cm^{-2})- curve 1 and by the Ar (E=46 MeV, $Ft = 8 \times 10^{14} cm^{-2}$)- curve 2 are presented.

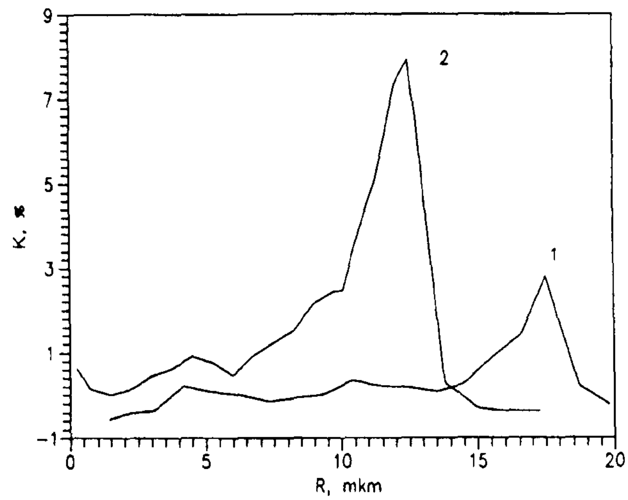

Fig.5. The distribution of the relative change of reflection coefficient k of Si samples by the ion range (curve 1- B and curve 2- Ar).

One can see that in regions from 15μ to 20μ and from 6μ up to 14μ there are peaks with maxima at $R = 17.5\mu$ and $R = 12.5\mu$. These peaks are caused by the elastic losses of the ions energy of B and Ar and are connected with partial amorphization of these regions that leds to the change of reflection coefficient. It is shown that the amorphization degree for the Ar ions is essentially higher with a less fluence than for B. This is connected with differencies in production defect cross-section.

For the investigation of the role of elastic and inelastic energy losses the structural and mechanical properties of the model ionic crystal LiF, irradiated with ions Xe (118 MeV), Ar (225 MeV and 46 MeV), Ne (113 MeV) and Ne (27 Mev) at 10^{10}- $10^{14} cm^{-2}$ dose range were stidied by using spectrophotometric and microhardness technique.[10)] The comparison of the total number of anion vacancies from absorption spectra by using the Smakula equation with the data obtained from the E-DEP1 program, it was shown that the total number of anion vacancies is determined generally by the total ionization energy losses of heavy ions. The observed differences in dose dependences of point defect concentrations for Xe, Ar, Ne beginning after a certain dose may be explained as a result of the ion track overlapping. It's increases the annealling of point defects in track's region taking into account the high value of electronic stopping power for heavy ions with $1MeV/a.m.u.$ energy.

The change of mechanical properties of LiF crystals as shown is determined by the radiation damages caused by the elastic collisions of bombarded ions with the lattice atoms.

2.5. THE LUMINESCENCE OF CRYSTALS IRRADIATED WITH $1MeV/a.m.u.$ HEAVY IONS

In distinction from the traditional methods of luminescence the high energy ion beams induced luminescence can allow to study the structure of materials during the formation and further evolution of radiation damages. In this case the radiation damages are created by elastic losses $(dE/dx)_{el}$ and the excitation of the luminescence centres - by electronic losses of ion energy $(dE/dx)_{inel}$.[11] The luminescence spectra of an unalloyed LiF single crystal during Ar (46 MeV) bombardment at various fluence are shown in Fig.6.

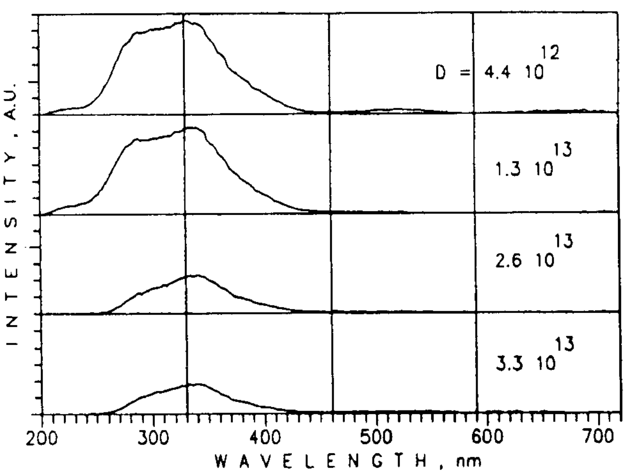

Fig.6.The intensity/wave length dependence of LiF luminescence during Ar bombardment.

In this spectra a series of width bands are seen. The intensity of this bands strongly depends from ion fluence and decrease to phone values for a long-wave band ($\lambda_{max} = 670nm$), which occurs by the F2-centres. This band isn't observed in ealier investigations by using low energy ions excitation. Luminescence yield in the bands with $\lambda_{max} = 335$ and 515 nm is a result of a recombination of V_k and V_F centres with free electrons and electron F-centres arising during ion bombardment. Also, the difference in temperature dependences of luminescence intensity between low and high energy ion bombardment is observed.

2.6. THE RADIATION STABILITY OF SEMICONDUCTOR DEVICES

The electron devices being a long period of time in the field of ionizing radiations are subjected to significant radiation loads leading to their breakdown or impossibility of realization of their functional tasks. This concerns both devices acting in reactors and semiconductor devices operating in cosmic space.

Application of heavy ion accelerators for spectra simulating of cosmic radiation, influence of neutrons and other types of radiation seems to be a promising one.

The ion beams of the most different energies and masses provide wide possibilities to carry out such investigations. In this paper we consider one of the examples of such works, notably, the investigation of errors accumulation of time and energy dependences of the microcircuit memory cells of operative memory while irradiation by the ions B, O and Ne with the energy of $1MeV/a.m.u.$.[12] To decrease the density of ion flux there was applied a scattering chamber, in which the ions were being scattered on thin gold foil and reached the integral microcircuit and semiconductor detecter positioned at angles of 30^o to the beam axis. In Fig.7 there is the dependence of errors member on time while irradiation of memory cell, by capacity 4098, ions O and Ne with the energies of 19 MeV and 27 MeV, respectively. The transition of memory cell from state "1" into state "0" is considered as an error.

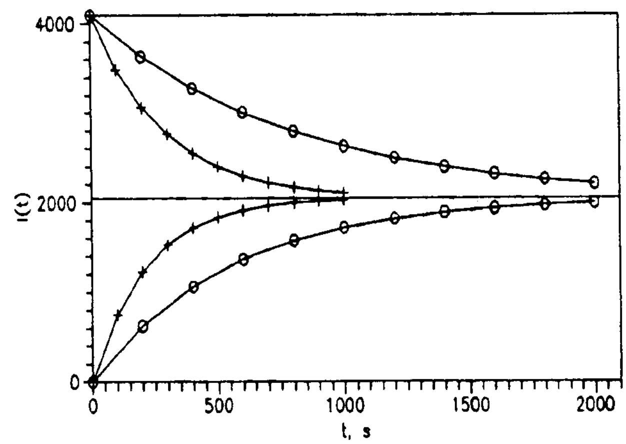

Fig.7. The errors member versus time for null and unit back ground state of memory cells for O (+) and Ne (o).

As seen, the effect manifestation has a nature close to exponential one and is approximated by the following expressions: $L(t) = A(1 \pm exp(-FSt))$, where sign "-" relates to the null background state and sign "+" - to unit one, A= 2048, S- effective square of memory cell, and F- density of ion flux.

2.7. RADIATION RESEARCHES OF POLYMERIC MATERIALS. TRACK MEMBRANES

By creation of detectors of heavy charged particles (fragments of nuclei fission) in which tracks manifested themselves by the following chemical etching there has been appeared a new direction namely the production of track membranes from different polymers with the use both the products of uranium nuclei fission (reactor method of membrane production) and on heavy ion accelerators.[13] The main advantage of this method is the energy homogeneity of ion beams that provides a possibility to have relatively low dispersion by pore diameters of track membranes ($\gamma = \Delta d/d$) and a wide choice of ions of different energies for polymeric materials irradiation from 10μ to 100μ of thickness.

In FLNR for irradiation of polymeric materials there are used heavy ions beams Kr with energies up to 300 MeV and in prospect (by putting the accelerator complex U-400+U-400M in operation) up to U.

The applications for track membranes production from chemically and radiative stable ion polymers with high specific ionizing energy losses (by performing the conditions of $(dE/dx)_{inel} \geq (dE/dx)_{lim}$ - registration threshold of the given particle in polymer) allow one to produce, first, pores with small sizes ($d < 0.1\mu$) and, secondly, with a low value of dispersion of pore diameters ($\gamma < 0.05$).

2.8. CONCLUSION

In the given review there are presented only partial directions of investigations on heavy ion beams with the energies exceeding 1 MeV/a.m.u. At the same time it is seen that "professions" of heavy ions are enough extended and regions of their application are various.

On the whole it is worth to mention that heavy ion accelerators are a good instrument in the investigations of condensed metter and radiation solid state physics.

3. REFERENCES

1) S.P.Vagin, A.Yu.Didyk, V.F.Reutov, V.A.Skuratov. "Pe- culiarity of Copper Radiation Swelling Irradiated by Xenon and Copper Ions with Energy 1 MeV/a.m.u. "Preprint JINR R14-88-440, 1988, Dubna.
2) A.Yu.Didyk, V.R.Regel, V.A.Skuratov, N.Yu.Mikhailova. "Radiation hardening of metals irradiated with heavy ions". Journal of Technical Phys., 1989, **59**, N5, p.107-111.
3) A.Bermudes, A.Yu.Didyk, V.N.Chernikov, V.A.Skuratov. "New cross-section method for investigation of heavy ion irradiation effects." In.: Abstracts of International Conference on Physics of Irradiation Effects in Metals, Hungary, 1991, p.W-12.
4) L.I.Gomozov, A.Yu.Didyk, T.N.Zvereva, I.L.Sashin, V.A.Skuratov. "Radiative-annealing hardening of vanadium. Phys. Metals and Metallovedenie", 1990, N7, p.160-168.
5) L.I.Gomozov, S.N.Votinov, A.Yu.Didyk et al. "Heavy Ion and Neutron Irradiation Effects on Vanadium Alloy Behaviour at post Radiative Annealing." Preprint JINR 14-86-409, 1986, Dubna.
6) A.Bermudes, A.Yu.Didyk, V.A.Skuratov. "Structure and Mechanical Properties of Metals Irradiated with $1 - 1.2 MeV/a.m.u.$" In.: Abstracts of International Conference on Physics of Irradiation Effects in Metals, Hungary, 1991, p.W-3.
7) J.F.Ziegler, J.P.Biersack, U.Littmark. "The stopping power, and range of the ions in solids". **1**, Pergamon Press, New, Jork, 1984.
8) C.M.Davisson and I.Manning. Adaptation of the program for, depth distribution of energy deposition by ion bombardment:, better stopping powers.- Comp.Phys.Comm., 1986, **42**, p.137-147.
9) A.Yu.Didyk,A.M.Zaitsev,S.A.Karamian. "Shift Ar^{40} and Xe^{129} on the Diamond Monocrystal". JINR Rapid Comm., N 4/37/-1989.
10) A.Yu.Didyk, R.Ts.Oganessian, V.R.Regel, V.A.Skuratov. "Influence of nuclear and ionization energy losses on damage production in crystals". Phys.Tverd.Tela, 1989, **31**, p.17-21.
11) D.V.Akinshin, A.Yu.Didyk, V.A.Skuratov. "The luminescence of crystals irradiated by 1 MeV/a.m.u. heavy ions". JINR Rapid Communication, 4/43/-90, 1990,p.48-55.
12) D.V.Akinshin, M.N.Borisova, N.G.Goleminov et al. "Use of MOS RAM for control of heavy ions flux". Device and technique of experiments, 1990, N 6, p.49-50.
13) G.N.Flerov, P.Yu.Apel, A.Yu.Didyk et al. "The use of heavy ion accelerators for the production of nuclear track membranes," Atomic energy, 1989, **67**, p.274-280.