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Investigations of positron lifetime spectra in iron defected with highly energetic Bi and Kr ions

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Abstract. The positron lifetime spectra in iron defected with a beam of Bi^{+51} and Kr^{+27} ions of energies 670 MeV and 240 MeV, respectively, were investigated. These spectra were analysed by an appropriate separation in 1, 2 or 3 components. It has been found that the experimental data best fit to the assumed model if only two components are taken into account. For comparison, we investigated both irradiated and non-irradiated surfaces of the sample. We have taken into account the fact that the range of penetration of iron by Bi and Kr ions is small. The dependence of the positron lifetime spectra on the absorbed dose and kind of the bombarding ions is presented.

Key words: ion implantation • defects • annihilation

Introduction

Since many years, the methods based on positron annihilation have been successfully used in studies of the creation and kinetics of defects in crystals [11, 12]. These methods are particularly useful in investigating the equilibrium point defects, moreover, they yield a valuable information on greater, in an atomic scale, defects [10]. The interpretation of the results is basing on the assumption that the defects are uniformly distributed in a sample.

However, in industrial and laboratory practice one often meets materials where the distribution of the defects is not homogeneous, e.g. subsurface defects, the defects produced during chemical reactions or created when implanting energetic ions into a metal.

One of the techniques commonly used in the investigation of these materials is the measurement of positron lifetime. The interpretation of the obtained results is not easy, in particular, if it concerns the samples of non-uniform distribution of defects. There are relatively many theoretical and experimental studies concerning defects created by light-charged particles of energies of the order of few MeV, like, e.g. protons, α-particles, deuterons. However, investigations concerning the mechanisms and spatial distribution of defects created during the implantation of high-energy ions in metals are rather scarce. Their results indicate that the kind, concentration and spatial distribution of these defects depend on the crystalline structure and microstructure of metal as well as on the energy and mass of the implanted ions.

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Experimental investigations evidence that after implantation the defect structure of the surface layer of metal is similar to that formed by plastic deformation (e.g. uniaxial tension). These layers are strongly stressed and the defects created in them are highly mobile. The final defect structure of such a metal is a result of defect migration and dislocation dynamics. A very important result of the investigations is the statement that implantation causes an increase in the defect concentration also in the regions deeper than the implantation depth [1–5, 7, 9, 13–15]. Such defects can be met in walls of nuclear reactors and accelerators. They distinctly change the physical properties of the technical devices.

This paper presents the results of investigations of positron lifetime spectra in iron defected by a beam of Bi^{+51} and Kr^{+27} ions.

Preparation of the samples

The investigated samples of dimensions $10 \times 10 \times 1$ mm^3 were prepared from an iron sheet of 99.994% purity. The surfaces of the samples were cleaned with methanol. Next, the samples were tempered for 8 h in vacuum ($p < 10^{-5}$ torr) at 800 K and then slowly cooled to room temperature (with a speed of 0.8 K/min). In prepared samples the positron lifetime spectra were investigated (from both sides of samples). Then, the samples were placed under a beam of Bi or Kr ions in a U-400 accelerator of Joint Institute for Nuclear Research in Dubna (Russia). The energies of Bi and Kr ions were 670 and 240 MeV, respectively. The doses of Bi ions were 5×10^{10}, 1×10^{12}, 5×10^{12} and 1×10^{14} cm^{-2} for Kr ions. Only one side of the samples (A) has been defected. The temperature during the irradiation process has been stabilized at 293 K. After irradiation, the positron lifetime spectrum was determined anew using a fast-slow type positron lifetime spectrometer (230 ps resolution). Both sides, irradiated (A) and non-irradiated (B) have been studied. The typical "sandwich" geometry was used, e.g. a ^{22}Na source was planted between two surfaces of the same type, AA or BB. The registered positron lifetime spectra were analysed using the Lifetime (LT) program [6]. Decomposition of each of the spectra into 1, 2 and 3 components has been controlled by χ^2 test. It has been found that in all cases the decomposition into two components assures the good fit to the experimental data.

Analysis and interpretation of the results

We investigated the positron lifetime spectra of both sides of the sample, from the irradiated and reversed, non-irradiated sides. As it is known from the computer simulation, carried out using the SRIM-2008 program, the ranges of penetration of the samples by Bi^{+51} (670 MeV) and Kr^{+27} (240 MeV) are 17.1 μm and 12.9 μm, respectively. Thus, the samples have been damaged approximately in these ranges which are rather small in comparison to the thickness of the tested material. The average depth of the penetration of the specimen by positrons emitted by the ^{22}Na source is 22 μm, but only about 0.1% from them reaches the depth 0.25 mm. Therefore, we expect that the results yielded by positron lifetime measurements give the information on physical processes having place in deeper layers than the range of the ions defecting the iron sample. The interpretation of the results is, however, difficult and requires a comparison to the spectra of non-irradiated side of the sample. The existence of two components, with different lifetimes τ_1 and τ_2 and two corresponding intensities I_1 and I_2, can be interpreted if one assumes that positrons annihilate from the free states in the bulk (lifetime τ_f) and from trapped states in defects of one type (lifetime τ_{D_1}). In this model, the longer lifetime τ_2 is equal to τ_{D_1} however, the lifetime τ_1 is shorter than τ_f. Certainly, if there are many mechanisms of the annihilation, we should apply the multistate model with a greater number of parameters. In many cases, however, the spectrometer resolution is insufficient for the separation of all the components of the analysed spectrum. In such situations one of the component obtained by the analysis of the registered spectrum is a result of the combination of two actual components with similar lifetimes. A comparison of the values of the positron lifetimes obtained in the present study with the literature data for pure iron, and for voids or large-size defects, suggests that in our case the component with shorter $\tau_{1,\mathrm{exp}}$ is, in fact, a combination of two components τ_f and τ_{D_1}.

According to the literature data, in iron the mean lifetime for positrons annihilating in the free state is about 102 ps, whereas that for positrons trapped in vacancies it amounts to about 150 ps, and for those annihilating in dislocations ranges from 117 to 140 ps, depending on the location of the trapping site [8, 10]. In turn, the component with a longer lifetime $\tau_{2,\mathrm{exp}}$ corresponds to the annihilation in defects of large sizes (e.g. multivacancy clusters and voids) [8]. Then:

$$\tau_{1,\mathrm{exp}} = \frac{I_f \cdot \tau_f}{I_f + I_{D_1}} + \frac{I_{D_1} \cdot \tau_{D_1}}{I_f + I_{D_1}} \tag{1}$$

and

$$\tau_{2,\mathrm{exp}} = \tau_{D2}, \quad I_{2,\mathrm{exp}} = I_{D2} \tag{2}$$

In the analysis of positron lifetimes in the defected samples we often use the following description of the mean positron lifetime in defects:

$$\tau_m = \frac{\tau_{1,\mathrm{exp}} \cdot I_{1,\mathrm{exp}} + \tau_{2,\mathrm{exp}} \cdot I_{2,\mathrm{exp}}}{I_{1,\mathrm{exp}} + I_{2,\mathrm{exp}}} \tag{3}$$

In Fig. 1, we present the changes of mean positron lifetime in iron defected with Bi^{+51} and Kr^{+27} ions in relation to the absorbed doses of radiation. The first point in this figure (and in the next drawings) presents the value of the positron lifetime that we obtained before the sample had been defected, i.e. immediately after the annealing of the sample. The points connected by a solid line correspond to iron irradiated with Bi^{+51} ions. The last points on the figures refer to Kr^{+27} irradiated iron. It is visible from the figure that for Bi^{+51} the mean positron lifetime measured from non-irradiated side (B) does not change, within the limits of error, while it increases with the dose of radiation when measured from the irradiated side (A).

For iron irradiated with Kr^{+27}, the average positron lifetime measured from the B-side is, in the limits of

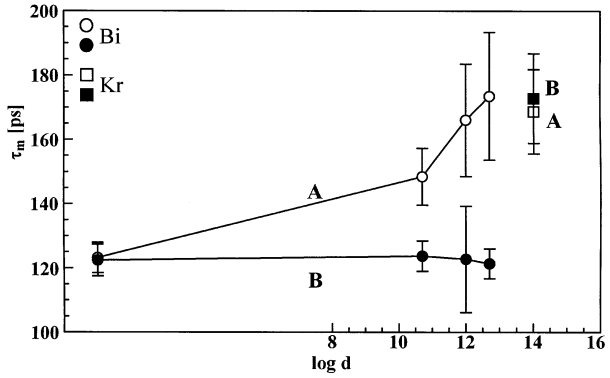

Fig. 1. The dependence of the mean positron lifetime in iron defected with Bi^{+57} and Kr^{+27} ions on the absorbed dose of the radiation (explanation in the text).

the experimental error, the same as that measured from the A-side, although layer than that measured before the sample irradiation. It seems, that this results from strong stresses in the crystal lattice of iron, caused by the presence of Kr ions of relatively large dimensions. Such stresses may lead to the creation of additional lattice defects located in the deep regions of the sample.

The dependences of the positron lifetime $\tau_{2,exp}$ and the intensity of the component $I_{2,exp}$ on the dose of radiation are presented in Figs. 2 and 3. One can notice that if the measurement was performed from the irradiated side of the sample, and dose of Bi^{+51} ions was greater than 1×10^{12} cm^{-2}, the value of the $\tau_{2,exp}$ component was

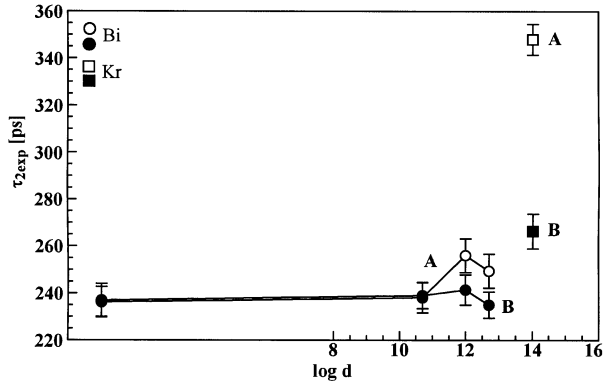

Fig. 2. The dependence of the $\tau_{2,exp}$ component in the lifetime spectrum of the positron annihilating in iron defected with Bi^{+57} and Kr^{+27} ions on the absorbed dose of the radiation (explanation in the text).

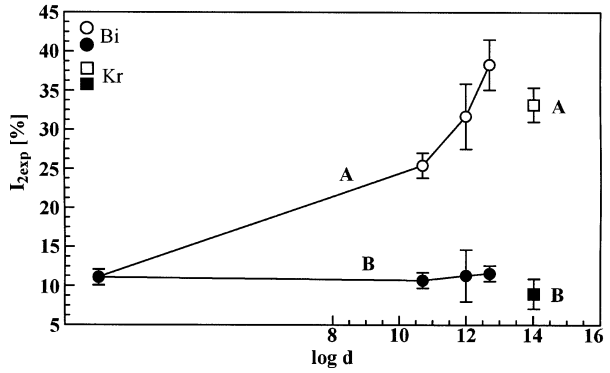

Fig. 3. The dependence of the intensity $I_{2,exp}$ of the long-living component in the lifetime spectrum of the positron annihilating in iron defected with Bi^{+57} and Kr^{+27} ions on the absorbed dose of the radiation (explanation in the text).

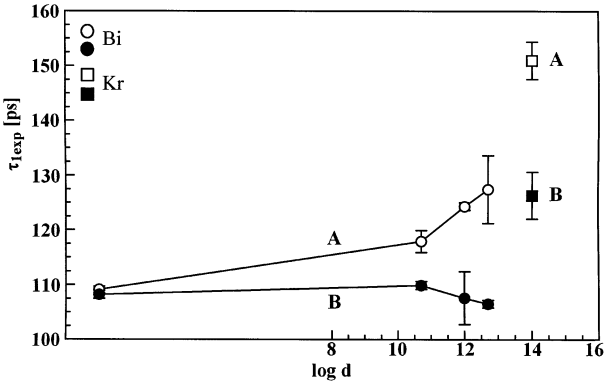

Fig. 4. The dependence of the value $\tau_{1,exp}$ of the short-living component in the lifetime spectrum of the positron annihilating in iron defected with Bi^{+57} and Kr^{+27} ions on the absorbed dose of the radiation (explanation in the text).

greater than the corresponding component measured from the non-irradiated side B. The value of the latter component does not overcome the limits of the error, independently of the dose of the absorbed ions at the side A. This means that dose of irradiation greater than 1×10^{12} cm^{-2} produces many neighbouring vacancies which, in turn, join in clusters containing about 10 vacancies. The enlargement of the intensity of the corresponding component with the magnitude of radiation can be explained by the appropriate increasing of the concentration of defects.

In the case of the samples irradiated with Kr^{+27} ions, this is possible that the formed clusters have greater sizes than the ones created by Bi^{+51} ions. There arise clusters even in such parts of the sample that could not be reached by Kr^{+27} ions, although the sizes of these clusters are smaller. We suppose they are produced by the secondary electrons following the Kr^{+27} ions moving through the sample.

Much more difficult in the interpretation are the changes of $\tau_{1,exp}$ values with the absorbed dose of radiation (Fig. 4). For iron defected with Bi^{+51} ions, the values of this component measured from the non-irradiated side are within the limits of error, independently of the absorbed dose of radiation. If, however, we measure $\tau_{1,exp}$ from the irradiated side, the corresponding values grow with the dose of radiation. In our opinion, this is caused by an increase of the concentration of monovacancies created by Bi^{+51} ions crossing the sample (see Eq. (1)). The values of $\tau_{1,exp}$ are greater for iron irradiated with Kr^{+27} ions than for the sample irradiated with Bi^{+57} ions.

It seems understandable, since hundred times greater dose of Kr^{+27}ions absorbed by iron, produces much more vacancies than Bi^{+51} ions. The secondary electrons following the Kr^{+27} ions additionally create some vacancies, even in the part B of the sample.

The results presented in this paper are only preliminary. The full explanation and interpretation of the results requires, however, some additional studies.

Conclusions

1. Irradiation of iron with highly energetic beam of Bi^{+51} and Kr^{+27} ions causes the formation of the two kinds of defects: multivacancy clusters and monovacancies.

2. The concentration of both kinds of defects created at the irradiated surface of the sample increases with the absorbed dose of radiation.
3. Kr^{+27} ions produce, finally, the clusters of greater sizes than do the more energetic Bi^{+51} ions.
4. After implantation of high-energy Bi^{+51} and Kr^{+27} in iron appear the defects located far from the implantation depth.

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