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METHODS FOR OBTAINING A UNIFORM VOLUME CONCENTRATION OF IMPLANTED IONS

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While solving many problems of radiation material science connected with investigation of behaviour and influence upon the structure and properties of structural materials of transmutation impurities, in particular atoms of helium and/or hydrogen, their irradiation by high energy (tens of MeV) alpha-particles and protons is used. One of the major advantages of high energy particles is their possibility to penetrate into objects for great depths (hundreds of microns). However, peculiarities of physics of damage and ion alloying by high energy particles do not provide conditions of uniform formation of radiation defects and storage of ions along the path of movement of the particles in the sample. Thus it is necessary to use the special variations of irradiation methods. In paper [1] an overview of available methods of formation of uniform volume concentration of implanted ions is given. One or another method of changing range of the projectiles in a sample material is at the basis of the methods. The method of changing the particle range due to the change of the angle of their incidence onto the surface of the sample during its inclination, suggested by the author, needs special regulation of rate of the sample rotation following a complex law by means of a computer. A set of thin absorbent foils or varying thickness absorbent filters, for example, in the shape of a wedge [2], are used more often. However, there is a major disadvantage of these methods, i.e. the difficulty of production of the absorbent filters.

Three simple practical methods of irradiation with high energy particles, providing the conditions of obtaining a uniform volume concentration of the implanted ions in the massive samples are described in the present paper.

Realization of the condition of two-sided irradiation of a plane sample during its rotation in the flux of the projectiles is the basic of the first method, excluding the use of a computer to regulate rates of inclination of the irradiated sample.

The conditions needed for obtaining a uniform volume concentration of implanted ions are:

- thickness of the irradiated sample must be equal to or less than the length of projective range of ions of given energy in a material,
- uniformity of the flux of the particles over cross-section of the beam incident to the sample which is obtained by its scanning over the sample surface,

- the size of ion beam must be no less than the area of the irradiated sample.

Two moments of irradiation of a plane sample for different angles of incidence of ion beam ($\varphi>0$ and $\varphi=0$) with flux density n_0 are shown in Fig.1. As it is seen, the depth of penetration of ions in the sample (x) is changed depending upon the angle of its turn (φ) following the law $x = R_0 cos\varphi$ (R_0 is the value of projective range of the particles) and width of straggling zone is $b = b_0 cos\varphi$. For this density of ion flux incident to the sample is changed according to the law $n = n_0 cos\varphi$, therefore an average concentration of ions in straggling zone is not changed as for as $n_0 cos\varphi / b_0 cos\varphi = n_0/b_0$.

If a function is introduced

$$\theta(y) = \begin{cases} 1 & for \quad y \geq 0 \\ 0 & for \quad y < 0 \end{cases} \qquad (1)$$

then the rate of alloying $d\rho(x)/dt$ in any point of the sample (x) can be defined in a common form:

$$\frac{d\rho(x)}{dt} = \frac{n_0}{b_0}\{\theta(x - R_0 cos\varphi) - \theta[x - (R_0 + \frac{b_0}{2})cos\varphi]\} \qquad (2)$$

where $\rho(x)$ is concentration of ions at the depth of the sample (x).

Having integrated this expression over time from 0 up $\pi/2\omega$ (ω is the rate of the sample rotation) we obtain concentration of ions at the depth of sample x during a quarter of a period:

$$\rho(x)_{T/4} = \frac{n_o}{b_o\omega}\left[\theta(R_o - x) arcsin\frac{x}{R_o} - \theta(R_o + \frac{b_o}{2} - x) arcsin\frac{x}{R_o + \frac{b_o}{2}}\right] \qquad (3)$$

To obtain a total number of implanted ions (N) over the whole thickness of the sample during a quarter of a period it is necessary to integrate the last expression over x from 0 up to ($R_0 + \frac{b_0}{2}$). We find that $N = n_0/\omega$, and average concentration of ions in the sample is

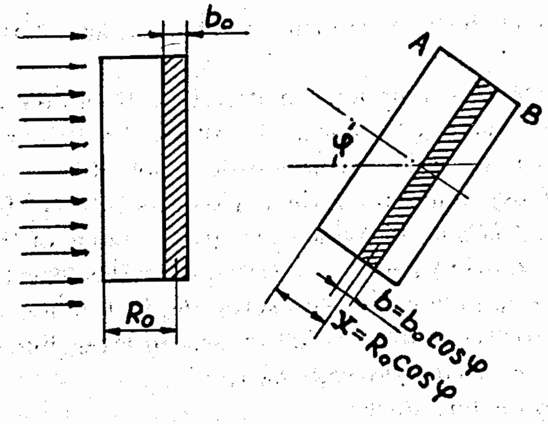

Fig.1. The change of depth (**x**) and width (**b**) of ion straggling zone while rotating samples.

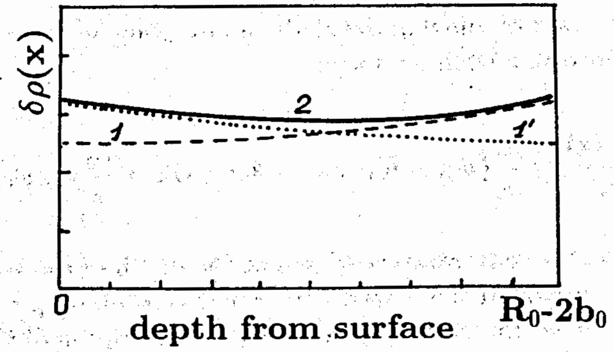

Fig.2. Profiles of the concentration ($\delta\rho$) in plane samples with thickness (R_o-$2b_o$) at rotation in the flux of projectiles: **1** and **1'** - at irradiation of the side of the planes **A** or **B**, respectivly, **2** - under conditions of continuous rotation.

$$\bar{\rho}_{T/4} = \frac{N}{R_0 + \frac{b_0}{2}} = \frac{n_0}{\omega(R_0 + \frac{b_0}{2})} \tag{4}$$

Then a relative concentration of ions obtained over x depth will be determined by the expression:

$$\delta\rho(x)_{T/4} = \frac{\rho(x)_{T/4}}{\bar{\rho}_{T/4}} = \frac{2R_0 + b_0}{2b_0}\left(\arcsin\frac{x}{R_0} - \arcsin\frac{x}{R_0 + \frac{b_0}{2}}\right) \tag{5}$$

The plot of this function is given in Fig.2 (curve 1). During irradiation of the sample from one side only concentration of alloying ions is greatly and non-linearly charged over the sample depth. However, after irradiation of the plane sample from its other side, i.e. after turn of the sample round its axis to an angle $\varphi=\pi$, we'll obtain a profile of the sample alloying by ions described by curve 2 as a result of superposition of curves 1 and 1$'$. If the sample of $t = R_0$-$2b_0$ thickness is irradiated, then scattering of ion concentration from an average value does not exceed 15%.

Thus, constant rotation of a plane sample in a flux of the projectiles provides conditions to obtain a uniform volume concentration of implanted ions in it.

The use of free air as a filter with varying absorbent ability due to the movement of the irradiated sample along ion beam brought to the atmosphere is at the basis of the second method of uniform ion alloying.

Fig.3 schematically shows the process of alloying a plane sample irradiated in the atmosphere by ion beam with intensity n_0. When the sample is moved with uniform rate V along ion beam in the direction, pointed by an arrow, the path of their range in air R is increased, decreasing by this the energy of ions incident on the sample. This causes decrease of depth of penetration of ions into the sample x, i.e. to movement of straggling zone in opposite direction with rate V.

Depth of penetration of ions x into the sample depends upon energy of bombarding ions, which in its turn is determined by length of their range in air R. In general form it can be written: $x = f(R)$, then

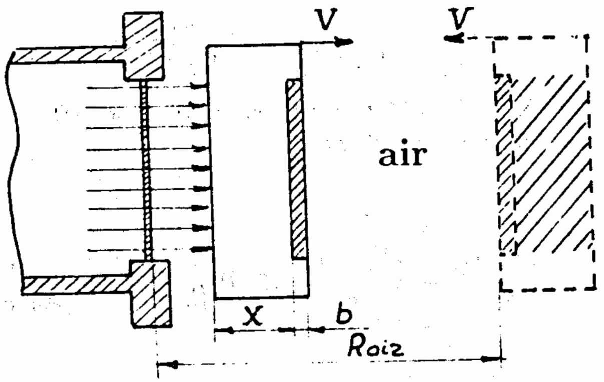

Fig. 3. The change of straggling zone depth under sample irradiation in the air with its reciprocating movement. R_{air} -ion range in the air, **x** - the depth of ion penetration into a sample, **b** - the width of particles straggling zone.

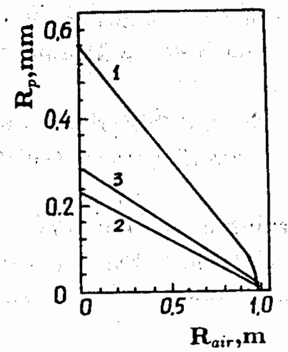

Fig. 4. The length of proton range (R_p) with energy of 9.45 MeV in **Al** (1), **Pb** (2) and **Cu** (3) versus their preliminary range in the air (R_{air}).

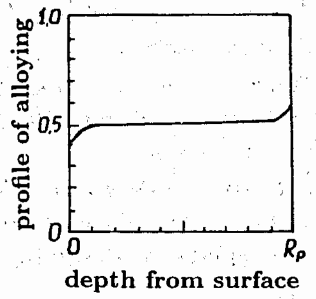

Fig. 5. Profile of ion concentration in a sample reciprocally moving in the ion flux directed into the air.

$$V(x) = \frac{dx}{dt} = \frac{dx}{dR} \cdot \frac{dR}{dt} \qquad (6)$$

$\frac{dR}{dt}$ is the rate of movement of the sample V.

Concentration of implanted ions at x depth is determined by the expression

$$\rho(x) = \frac{n_0}{Vdx/dR} \qquad (7)$$

Function $x = f(R)$ can be defined by a numerical method using curves "range-energy" of ions in air and a corresponding material of the sample. From Fig.4 it is seen that almost in a whole interval x, excluding boundary regions only, $dx/dR = const$. From here it follows that for uniform reciprocating movement of the irradiated sample along ion beam, brought to the atmosphere, the profile of their concentration in the sample has a uniform nature at the whole depth of alloying region practically (Fig.5).

The third method of obtaning a uniform volume concentration of the implanted ions in a massive sample excluding the labour - intensive process of the absorbent filters of varying thickness in the shape of a wedge consists of irradiation of a sample through the absorbent filter in the shape of a foil curve according to parabolic law moving along its surface.

Let us consider a case of irradiation of a plane sample through a foil of δ, thickness bent according to a definite law $y = f(x)$. The following scales of size are characterestic for this case: $R_0 \gg \delta \geq b_0$. In this case the filter thickness is determined by the expression:

$$Z^*(x) = \delta\sqrt{1 + (y'(x))^2} \qquad (8)$$

The shape of the curve $y = f(x)$ does not influence upon the value of concentration of the implanted ions in the straggling zone but it influences upon its spatial arrangement in the irradiated sample. Coordinate Z_1 of the middle of the straggling zone is determined from the ratio:

$$Z_1(x) = R_o - \delta\sqrt{1 + (y'(x))^2} \qquad (9)$$

To provide a uniform concentration of the implanted ions in the sample volume at depths $\leq R_0$ in the case of moving along the irradiated sample surface of bent foil it is necessary to specify a law of its bending, providing a linear dependence of change of foil thickness δ upon coordinate x, i.e. the condition $Z^*(x) = \gamma x + \delta$ must be fulfilled.

From ratio (8) it follows:

$$\delta(1 + (y'(x))^2)^{1/2} = \gamma x + \delta \tag{10}$$

where $\gamma = (R_0 - \delta)/x_m$, x_m is a coordinate for which the thickness of the bent filter must be equal to $\bar{R}_0$.

Equation (10) is integrated analytically.

An accurate solvation has a form:

$$y = \frac{\delta}{2\gamma}\{[(\frac{R_0}{\delta} - 1)\frac{x}{x_m} + 1]\sqrt{[(\frac{R_0}{b_0} - 1)\frac{x}{x_m} + 1]^2 - 1} - ln[(\frac{R_0}{\delta} - 1)\frac{x}{x_m} + 1] + \sqrt{[(\frac{R_0}{\delta} - 1)\frac{x}{x_m} + 1]^2 - 1}\} \tag{11}$$

Note that the second addend containing logarithmic dependence makes a significant contribution for small x only. For $R_0/\delta \gg x_m/x$ equation (11) is simplified and has the form:

$$y = \frac{\delta}{2\gamma}\left(\frac{R_o}{\delta} - 1\right)^2 \frac{x^2}{x_m^2} \tag{12}$$

The following condition must be fulfilled for the fact that the filter thickness is to be equal to R_0 in a definite point x_m:

$$\gamma \simeq \frac{R_o}{x_m}\sqrt{\frac{R_o - 3\delta}{R_o + \delta}} \tag{12a}$$

Ratios (12) and (12a) can be written in a more evident form:

$$y = \alpha x^2$$

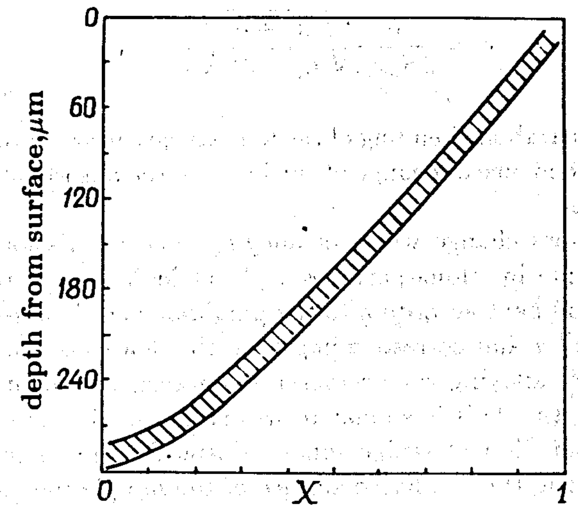

Fig.6. The change on the width of α-particles straggling zone with energy of 50 MeV and profile of the depth in molibdenum samples under its irradiation through absorbing foil curved according to parabolic law.

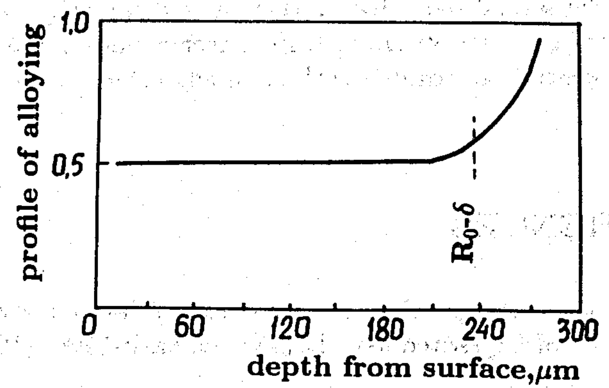

Fig.7. Profile of helium concentration by depth of molibdenum sample under α-particle irradiation with energy E=50 MeV through absorbing foil curved according parabolic law moving along the irradiated surface.

$$\alpha = \frac{\delta}{2R_o x_m}\sqrt{\frac{R_o+\delta}{R_o-3\delta}}\left(\frac{R_o}{\delta}-1\right)^2 \tag{13}$$

Thus, a parabolic bending of the foil satisfies necessary of obtaining a linear dependence of change of thickness of the absorbent filter upon coordinate x.

Fig.6 shows change width of alloying zone irradiation of molybdenum sample by alpha-particles with 50 MeV energy through the absorbent foil bent according to the parabolic low. It is seen that excluding small x and corresponding from the depths of alloying in the region (R_0-δ) alloying zone represents practically straight band with constant width. This is similar to irradiation of the sample through the absorbent filter of wedge shape. Naturally, during movement of this filter along the irradiated surface of the sample the conditions of obtaining a uniform volume concentration of the implanted ions are provided in its volume at (R_0-δ) depth (Fig. 7).

As it follows from the above-mentioned, all the methods are simple in practical realization. For this the first method is the most effective for obtaining a great number of the samples, for example, for mechanical tests, the second one – for irradiation in different gaseous media, and the third one – for obtaining high concentrations of the implanted ions under controlled (regulated) thermal and deformation conditions.

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Методы создания равномерной объемной
концентрации имплантированных ионов

В настоящей работе описаны три простых в практической реализации способа облучения высокоэнергетическими частицами, обеспечивающие условия создания равномерной объемной концентрации имплантированных ионов в массивных образцах. В основу первого способа, исключающего использование ЭВМ для регулирования скорости наклона облучаемого образца, положена реализация двухстороннего облучения плоского образца при его вращении в потоке бомбардирующих частиц. В основу второго способа положено использование атмосферного воздуха в качестве фильтра с изменяющейся поглощающей способностью за счет движения облучаемого образца вдоль пучка ионов, выведенного в атмосферу. Третий способ, исключающий трудоемкий процесс приготовления поглощающих фильтров переменной толщины в виде клина, состоит в облучении массивного образца через движущийся вдоль его поверхности поглощающий фильтр в виде фольги, изогнутой по параболическому закону. Первый способ наиболее эффективен для облучения большого количества образцов, например, для механических испытаний, второй — для облучения в различных газовых средах, а третий — для достижения высоких концентраций имплантированных ионов при контролируемых термических и деформационных условиях.

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Methods for Obtaining a Uniform Volume Concentration of Implanted Ions

Three simple practical methods of irradiations with high energy particles providing the conditions of obtaining a uniform volume concentration of the implanted ions in the massive samples are described in the present paper. Realization of the condition of two-sided irradiation of a plane sample during rotation in the flux of the projectiles is the basis of the first method. The use of free air as a filter with varying absorbent ability due to movement of the irradiated sample along ion beam brought to atmosphere is at the basis of the second method of uniform ion alloying. The third method for obtaining uniform volume concentration of the implanted ions in a massive sample consists of irradiation of sample through the absorbent filter in the shape of a foil curved according to the parabolic law moving along its surface. The first method is the most effective for obtaining a great number of the samples, for example, for mechanical tests, the second one — for irradiation in different gaseous media, the third one — for obtaining high concentrations of the implanted ions under controlled (regulated) thermal and deformation conditions.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.