**Introduction**

Unique properties of nanometer structures such as quantum dots, wires and so on have attracted great interest for some decades [1, 14]. One way of nanometer structuring of solids is swift heavy ion irradiation. Under the definite conditions it creates an ion tracks system in the form of narrow cylinders or nanometer cluster chains with modified structure embedded into undamaged matrix. The study of interaction of swift heavy ions with semiconductor single crystals is very important both for the fundamental investigations of radiation effects in condensed matter and for the creation of ion tracks in semiconductor materials, which can be used in modern nanotechnologies of electronics [2, 5–7, 13, 15].

In this paper we present a study of radiation damage in GaAs single crystals irradiated with $^{84}$Kr ions of energy $E_{Kr} = 394$ MeV up to the fluence of $5 \times 10^{12}$ ion/cm$^2$. The distribution of damage along the projected range of $^{84}$Kr ions in GaAs was investigated using selective chemical etching of a single crystal cleaved perpendicularly to the irradiated surface. The damage zone located under the Bragg peak of $^{84}$Kr ions was observed. Explanation of the observed effects based on possible processes of channeling of knocked target atoms (Ga and As) is proposed.

**Key words:** semiconductors • gallium arsenide • swift heavy ions • inelastic energy loss • atomic force microscopy (AFM) • ion channeling

---

**Damage distributions in GaAs single crystal irradiated with $^{84}$Kr (394 MeV), $^{209}$Bi (710 MeV) and $^{238}$U (1300 MeV) swift ions**

**Abstract.** We are presenting a study of damage distribution in GaAs irradiated with $^{84}$Kr ions of energy $E_{Kr} = 394$ MeV up to the fluence of $5 \times 10^{12}$ ion/cm$^2$. The distribution of damage along the projected range of $^{84}$Kr ions in GaAs was investigated using selective chemical etching of a single crystal cleaved perpendicularly to the irradiated surface. The damage zone located under the Bragg peak of $^{84}$Kr ions was observed. Explanation of the observed effects based on possible processes of channeling of knocked target atoms (Ga and As) is proposed.

**Key words:** semiconductors • gallium arsenide • swift heavy ions • inelastic energy loss • atomic force microscopy (AFM) • ion channeling
394 MeV and the ion fluence was \((\Phi \times t)_{Kr} = 5 \times 10^{12} \text{ ion/cm}^2\). The ion flux was \(\Phi_{Kr} \leq 5 \times 10^9 \text{ ion/cm}^2 \times c\) and the temperature of GaAs samples during irradiation was less then 30°C. The irradiated GaAs samples were cleaved perpendicularly to the irradiated surface (along the projected range of \(^{84}\text{Kr}\) ions). The damage depth distribution was visualized by the treatment of cleaves in a special selective chemical solution.

The surface of GaAs sample etched cleaves were studied using a scanning electronic microscope JSM-840 (SEM). The SEM studies showed the absence of radiation damage before the Bragg peak. The structures looked like “channels” were registered far under the Bragg peak (Figs. 1 and 2). The length of zone with visualized “channels” was about a half of \(^{84}\text{Kr}\) ion projected ranges. The surface density of “channels” was much less than the track density along the cross section of irradiated crystal should be. This density should be about \(N_{\text{cleaves}} \approx \sqrt{(\Phi \times t)_{Kr}} = 2.236 \times 10^6 \text{ cm}^{-1}\), and the mean distance between the “channels”-tracks should be \(R_{\text{track}} \approx 44.7 \text{ Å}\). It is clear that the observation of such low scale features is impossible using the estimation described above.

In accordance with the SEM results, the radiation damages like “channels” were observed under the Bragg peak and were absent before the Bragg peak where the inelastic energy loss should be high. One can conclude that it is impossible to explain the observed results as occurring owing to ionization losses of \(^{84}\text{Kr}\) only. The narrow damage zones with high defect concentration looked like a strongly etched single stripe (Fig. 1) and two stripes (Fig. 2) were observed at the depth of the maximum of nuclear (elastic) energy loss at \(Z_{\text{max}} \approx 30.5 \mu\text{m}\). As one can see, the wide etched layer lies under the Bragg peak and is characterized by a width of about 15 \(\mu\text{m}\) (Fig. 2). So, the damaged zone from the surface up to the end of the etched “channels” spreads up to the depth \(Z_{\text{damage}} \approx 1.5 \times R_e = 45 \mu\text{m}\). It is necessary to note that both Figs. 1 and 2 were obtained using different selective chemical etching solutions.

It is necessary to note that the GaAs samples were not oriented in the direction of initial ion beam, i.e. the direct axial ion channeling was excluded.

**Model of observed damage and discussion**

The results of calculations of the value of inelastic energy loss \((-\partial E/\partial Z)_{Kr}\) and values of damage dose near the surface \(D_{Kr}(Z = 0) = \sigma_{dKr}(Z = 0) \times (\Phi \times t)_{Kr}\) and at the Bragg peak \(D_{Kr}(Z = Z_{max}) = \sigma_{dKr}(Z = Z_{max}) \times (\Phi \times t)_{Kr}\) are presented in Table 1. Calculations were carried out using the computer code TRIM-2000 [4].

The maximum energies delivered by \(^{84}\text{Kr}\) to firstly knocked Ga and As atoms (FKA) have been calculated using the simple formula:

\[
E_{\text{Ga/As}}^{\text{max}} = 4 \times \frac{M_{Kr}}{M_{\text{Ga/As}}} \left( \frac{M_{\text{Ga/As}}}{M_{Kr} + M_{\text{Ga/As}}} \right)^2 \times E_{Kr}
\]

The projected ranges of FKA in a GaAs target have been calculated using the computer code TRIM-2000 [4]. The maximum energies and projected ranges of FKA are presented in Table 2.

As one can see, the experimentally measured depth position of narrow stripes (Figs. 1 and 2) \(Z = 30.5 \mu\text{m}\) is in agreement with the calculated projected range of

---

**Fig. 1.** SEM images of etched cross section cleave of GaAs sample irradiated with \(^{84}\text{Kr}\) ions \((E_{Kr} = 394 \text{ MeV}, (\Phi \times t)_{Kr} = 5 \times 10^{12} \text{ ion/cm}^2)\). White arrow (left part of the photo) shows the narrow stripe of damage maximum at the Bragg peak. Right part of the photo predicts with the magnification \((\times 4)\) a region marked by rectangle on the left part of the photo.

**Fig. 2.** SEM image of two wide stripes (marked by the white arrows) near the Bragg peak and a wide damage layer with the width of about 15 \(\mu\text{m}\) under the Bragg peak.
Damage distributions in GaAs single crystal irradiated with $^{84}$Kr (394 MeV), $^{209}$Bi (710 MeV)...
ratios: 1:1.51:2.81, i.e. the mental projected ranges of ions should have the ratios: 1:0.66:0.36 (see Fig. 3 and Table 3 (1–3 lines)).

**Selective chemical etching of GaAs crystal cleaved along projected range of ions**

The results of atomic force microscopy (AFM) and selective chemical etching (SCE) for the samples of GaAs irradiated by swift $^{209}$Bi heavy ions with energy 710 MeV up to the fluence of $5 \times 10^{10} \text{ Bi/cm}^2$ were published in [18]. The images of GaAs irradiated surface and the profile of surface realized along the line 1–2 obtained by AFM are presented in Fig. 4.

One can see that the entrances of $^{209}$Bi heavy ions to the surface of GaAs samples have circular hillock forms with a diameter of $D_{\text{hillock}} \approx 15 \text{ nm}$, height $H_{\text{hillock}} \approx 0.5 \text{ nm}$ with the crater-like structures at the center of each hillock (Fig. 4).

The calculations of temperature inside the $^{209}$Bi swift heavy ion track volumes using a thermal spike model and taking into account the dependence of thermophysical parameters vs. temperature and without any free parameters [3, 20] allowed to conclude that the amorphous track volumes can be produced with a maximum radius of about $R_{\text{melt}} \approx 8.8 \text{ nm}$, this means that the maximum radiiuses of melted zones are about 8.8 nm and their existing time is $\tau \approx 8 \text{ pc}$. Surface density of such hillocks is about $3.5 \times 10^{10} \text{ hillock/cm}^2$ and this value is in quite good agreement with the ion fluence. SCE allows to observe the steeps of tracks on the splits of GaAs samples irradiated with U (1300 MeV) and Bi (710 MeV) heavy ions at a fluence of $5 \times 10^{10} \text{ ions/cm}^2$. The track ion
Damage distributions in GaAs single crystal irradiated with $^{84}$Kr (394 MeV), $^{209}$Bi (710 MeV),... TEM). The same effect was registered during the study of Xe track in GaAs (100) by the scanning tunneling method (STM) [11].

The use of SCE allowed us to observe U and Bi ion tracks in GaAs. Nevertheless, the amorphous tracks were not registered by our TEM studies. This may be caused by annealing processes under the influence of electron beam of high voltage electron microscope.

The authors of an excellent paper [11] have investigated the track structures in p-type GaAs bulk crystals irradiated under normal incidence to the (100) 3.54 GeV Xe$^{31+}$ ions up to the fluence $2.5 \times 10^{11} \div 5.0 \times 10^{11}$ ions/cm$^2$ using STM and scanning tunneling spectroscopy (STS) methods. STM images of the cleavage (110) surfaces revealed the fine structure of a single ion track consisting of a long straight linear defect of $D_{core} \approx 5$ nm in diameter sheathed with a thin fringe in bright contrast. STS study allowed concluding the phase composition, position of Fermi level and local electron density conditions of core and periphery of track. The tracks consist of an amorphous core with a diameter of $D_{core} \approx 5$ nm surrounded by an irregular region extending over a distance of $\approx 40$ nm. The band gap of irregular region surrounding the track core kept the same value as in undamaged matrix, meaning that the crystal structure was preserved into this volume. However, this region is characterized by a different position of the Fermi level relatively to the zone edge and a different local density of state at energetic zones in comparison with undamaged matrix. As it was shown earlier, the AB-etchant (CrO$_3$:H$_2$O:HF:AgNO$_3$ [6]) is able to reveal areas with changed energetic positions of the Fermi level and local densities of electronic states. We can suppose that selective etching of irradiated samples allows to reveal destroyed areas around the cores of ion tracks.

The energies ($E$), projected ranges ($R_p$), inelastic energy loss ($S_{inel} = -(\delta E/Z)_{inel}$), damage cross section creation $\sigma_d$ ($Z = 0$) and $\sigma_p$ ($Z = R_p$) for $^{209}$Bi, $^{238}$U, $^{129}$Xe and $^{84}$Kr ions at GaAs single crystal are presented in Table 4.

For estimations of maximum lattice temperatures at track axis near the surfaces of GaAs crystal samples for $^{84}$Kr$^{36+}$ (394 MeV), $^{129}$Xe$^{54+}$ (3.54 GeV) and $^{238}$U$^{92+}$ (1.3 GeV) was used the simple expression:

$$ T_{lattice}^{ion} = T_{lattice}^{Bi} \times \frac{S_{inel}^{ion}}{S_{inel}^{Bi}} $$

For comparison of temperature effects at ion tracks, it is not so bad approximation, because the temperature dependences and values of thermophysical parameters for electron subsystems are very difficult to be calculated or estimated, so the mistakes in the calculations

<table>
<thead>
<tr>
<th>Kind of ion</th>
<th>Energy (MeV)</th>
<th>$R_p$ (µm)</th>
<th>$S_{inel}^{Bi}$ (keV/µm)</th>
<th>$\sigma_d$ ($Z = 0$) (dpa × cm$^2$/ion)</th>
<th>$\sigma_p$ ($Z = R_p$) (dpa × cm$^2$/ion)</th>
<th>$T_{lattice}^{Bi}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{209}$Bi</td>
<td>710</td>
<td>34.8</td>
<td>38.3</td>
<td>$4.84 \times 10^{-10}$</td>
<td>$8.83 \times 10^{-45}$</td>
<td>2480 [20]</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>1300</td>
<td>41.2</td>
<td>44.0</td>
<td>$2.08 \times 10^{-16}$</td>
<td>$9.86 \times 10^{-45}$</td>
<td>$= 2850$</td>
</tr>
<tr>
<td>$^{84}$Kr</td>
<td>394</td>
<td>30.4</td>
<td>15.4</td>
<td>$3.51 \times 10^{-17}$</td>
<td>$3.87 \times 10^{-45}$</td>
<td>$= 1000$</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>3540</td>
<td>178.6</td>
<td>16.1</td>
<td>$1.82 \times 10^{-16}$</td>
<td>$4.17 \times 10^{-45}$</td>
<td>$= 1040$</td>
</tr>
</tbody>
</table>

Fig. 4. AFM – lateral-force image of GaAs surface irradiated with $^{209}$Bi ions of energy 710 MeV up to the fluence of $5 \times 10^{10}$ Bi/cm$^2$ (a) and the profile of surface realized along the line 1–2 (b). The AFM scanning square is equal to 420 × 420 nm$^2$.
of track temperatures using thermal peak model can be large. The presence of “entrance” places of $^{129}\text{Xe}$54+ swift heavy ions on the surface and long straight linear defects consisting of a core and an irregular region around it, along the projected ranges (cross-sectional method for the study by STM of cleavage surfaces) in spite of the estimations of temperatures on the track axis (see Table 4) allows to conclude that the temperature at ion tracks under the $^{129}\text{Xe}$54+ and $^{84}\text{Kr}$36+ irradiation of GaAs single crystal should be higher than $T_{\text{track}} = 1510$ K.

Conclusion

1. The experimentally measured value of projected range (or more precisely – the position of Bragg peak) of $^{84}\text{Kr}$5+ ions with energy $E_{\text{Kr}} = 394$ MeV in a GaAs single crystal [100] is in agreement with the calculated one.

2. The strong etched zone consisting of two narrow stripes (see Fig. 2) are situated at the distance $\Delta Z = 3.1$ μm. The area between the stripes is practically not etched. It can be connected with the so-called thermal spike effects in low-energy single-ion impacts [17, 19].

3. The broad zone of strongly etched structures looked like “channels” lying under the Bragg peak (Figs. 1 and 2) was registered. This may be explained by capturing by regime of axial channeling of $^{84}\text{Kr}$ ions after a few collisions with not very high energy delivering in each collision and Ga and As FKA with high energies ([9, 10, 16], where reported was experimental evidence for the redistribution of an isotropic ion flux after transmission through thin crystals).

4. The absence of etched structures before the Bragg peak may be explained by annealing of previously created ion tracks by following the passage of next $^{84}\text{Kr}$ ions due to thermal spike effect, which can cause heating of lattice up to temperatures sometimes more than the melting temperature of GaAs ($T_{\text{melting}} = 1510$ K) [20]).

Acknowledgment. This study was supported in part by the Belarusian Republican Foundation for Fundamental Research (Grant no. T06R-198).

References

3. Amirhanov IV, Didyk AYu, Muzafarov DZ et al. (2008) Application of the thermal spike model for explanation of variations of surface of highly oriented pyrolytic graphite under bombardment by $^{84}\text{Kr}$ and $^{208}\text{Bi}$ ions with high ionization energy loss. Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques 2;3:331–339