**Peculiarities of neutron interaction with boron containing semiconductors**

**Abstract.** The results of point defect creation calculation in B,C, BN and BP semiconductor single crystals irradiated in the fast neutron reactor IBR-2 are presented. It has been shown that during the thermal neutron interaction with light isotope boron atoms (\(^{10}\)B) the damage creation by means of fission nuclear reaction fragments (\(\alpha\)-particles and \(^{7}\)Li recoil nuclei) exceeds the damage created by fast neutrons (\(E_n > 0.1\) MeV) by more than two orders of value. It has been concluded that such irradiation can create a well developed radiation defect structure in boron-containing crystals with nearly homogeneous vacancy depth distribution. This may be used in technological applications for more effective diffusion of impurities implanted at low energies or deposited onto the semiconductor surface. The developed homogeneous vacancy structure is very suitable for the radiation enhanced diffusion of electrically charged or neutral impurities from the surface into the technological depth of semiconductor devices under post irradiation treatment.

**Key words:** semiconductors • thermal neutrons • point defects • vacancies • damage concentration • thermal neutron fluence • cross-section of damage creation • fission fragments • lithium • helium • \(\alpha\)-particles • diffusion of impurities • homogeneity of damage and active impurities

**Introduction**

Studies of different types of irradiation and a comparison of its action in semiconductors is an object of interest for radiation physics [3, 10–12, 17] and for its potential applications in novel nanotechnologies. Radiation destruction, surface sputtering, changes of phase composition structure in solid solutions [17], amorphous phase production in initially crystalline structures, recrystallization and adhesion processes, atomic ion-beam mixing [3] in immiscible systems [10], heavy ion track creation [3, 10–12] have attracted steady attention during few last decades because of possible application of the observed effects for creation of new advanced materials.

At the same time, the problem of impurity doping of semiconductors is very important. Sometimes it is impossible to obtain the required concentrations and depth distribution of doping impurities during the semiconductor growth processes. Impurity doping of semiconductors is provided by direct low energy ion implantation (ions energy of the order of a few hundred keV) or the formation of thin impurity layer on the semiconductor surface followed by a long-time annealing.

Boron containing semiconductors like B,C, BN and BP and some other compounds are seldom studied by experimentalists because of poor purification methods and difficulty in exploiting their semiconductor properties [6, 8, 9]. However, most of such semiconductors has
radiation resistant properties and consequently can be used in strong radiation conditions as in nuclear reactors (see [6, 8, 9, 15] and references therein).

Creation of well developed vacancy structure with homogeneous vacancy depth distribution is a good possibility for the following diffusion redistribution of impurities into some semiconductors during post-annealing processes.

The purpose of this article is to demonstrate a possibility of creation of homogeneous vacancy distribution into boron-containing semiconductors (B:C (AIII-BIV), BN and BP (AIII-BV)), with enhanced concentration of light isotope boron atoms (^10B) under irradiation with thermal neutrons in the fast neutron reactor IBR-2.

Consideration of the influence of nuclear fission fragments on the damage creation in boron-containing semiconductors

Nuclear reactions of thermal neutron capture by light ^10B isotopes with subsequent decays to fission fragments (α-particles and ^7Li recoil nuclei) can be written as [2]:

(1.1) \( n + ^{10}\text{B} \rightarrow ^{7}\text{Li} + \alpha \), at \( p_1 = 0.93 \), \( Q_1 = 2.78 \text{ MeV} \)

(1.2) \( n + ^{10}\text{B} \rightarrow ^{7}\text{Li} + \alpha \), at \( p_2 = 0.07 \), \( Q_2 = 2.39 \text{ MeV} \)

where \( Q_1, Q_2 \) are the nuclear energy of reactions and \( p_1, p_2 \) are the probabilities of nuclear decay. The value \( Q_1 = 2.78 \text{ MeV} \) corresponds to a decay of the composed nuclei \((n + ^{10}\text{B})\) up to the ground states of ^7Li recoil nuclei, and the value \( Q_2 = 2.3 \text{ MeV} \) corresponds to a decay of the composed nuclei \((n + ^{10}\text{B})\) up to the excited states of ^7Li recoil nuclei [2].

Parameters of interactions of α-particles and ^7Li recoil nuclei with subsequent decays to fission fragments (α-particles and ^7Li recoil nuclei) can be written as [2]:

\[
\alpha + \text{N} \rightarrow \alpha + \text{N}' + \text{Inel} + \text{Ed},
\]

\[
\text{Li} + \alpha \rightarrow \text{Li}' + \text{Ed},
\]

with \( Ed \) being the energy of the secondary particles and \( \text{Inel} \) the energy of inelastic excitation of the target nucleus.

All parameters have been calculated using a computer code TRIM-2000 [1].

The thickness of boron-containing semiconductors has been taken into account as being the same and equal to \( Z_{\text{max}} = 50 \mu\text{m} \). The threshold energy for displacement is assumed as \( E_d = 20 \text{ eV} \). The first value in the column for \( S_{\text{mel}}^\text{inel} \) (see Table 1a) corresponds to the value of inelastic energy loss near the decay places of the composed nuclei \((n + ^{10}\text{B})\) and the second one corresponds to the value of inelastic energy loss at the maximum of ionizing energy loss of α-particles, \( \sigma_{\text{mel}}^\text{inel} \) is damage creation cross-section at the maximum of elastic energy loss (Bragg peak) of α-particles and ^7Li recoil nuclei.

Point defect creation in amorphous Fe\(_7\)Ni\(_5\)Si\(_3\)B\(_2\) metallic alloy under the influence of fission fragments from nuclear reaction (1.1) was discussed in Ref. [7]. The alloy was irradiated with fission neutrons [16] in the fast neutron reactor IBR-2 using a “REGATA” channel of the so-called pneumatic post for transportation of samples to the reactor active zone of Frank Laboratory of Neutron Physics (FLNP) [5, 13, 14]. Calculations of damage creation were carried out under elastic scattering of fast neutrons at \( E_n > 0.1 \text{ MeV} \) and thermal neutrons at \( 0.01 \text{ eV} < E_n < 0.45 \text{ eV} \).

The relations between full neutron fluencies \( \Phi_n \) for different neutron energies are presented in Table 2 for the experimental conditions of amorphous alloy irradiation [7].

The calculated values of full numbers of light boron isotope atoms per cubic centimeter \( (N_{\text{boron}}) \) and the numbers of α-particles \( (N_{\alpha}) \) and ^7Li recoil nuclei \( (N_{\text{Li}}) \) produced by nuclear reaction (1.1) in semiconductors (BP, B:C and BN crystals) were obtained using the expression:

\[
N_{\alpha} = N_{\text{Li}} = N_{\text{Li}}' \times \sigma_{\text{capture}} \times \Phi_n^\text{thermal}.
\]

These values are presented in Table 3. The damage doses produced by α-particles \( (D_{\alpha}) \) and by ^7Li recoil nuclei \( (D_{\text{Li}}) \) at the layer with a thickness \( Z_{\text{max}} = 50 \mu\text{m} \) with a square of \( S = 1 \mu\text{m}^2 \) were obtained using the expression:

\[
D_{\alpha,\text{Li}} = N_{\alpha,\text{Li}} \times N_{\alpha,\text{Li}}' / N_{\text{Z_{max}}},
\]

Then, full damage dose can be presented as:

### Table 1a. Characteristic parameters of interaction of α-particles produced during nuclear reaction (1.1) with energy \( E_{n1} = 1.77 \text{ MeV} \)

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>( \rho ) (( \text{g/cm}^3 ))</th>
<th>( N ) (( \text{atom/cm}^3 ))</th>
<th>( T_{\text{mel}} ) (K)</th>
<th>( R_{\text{p}} ) (( \mu\text{m} ))</th>
<th>( N_{\alpha} ) (( \text{vac/Å} ))</th>
<th>( S_{\text{mel}}^\text{inel} ) (( \text{keV/Å} ))</th>
<th>( \sigma_{\text{mel}}^\text{inel} ) (( \text{dpa/cm}^2/\text{Å} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>2.89</td>
<td>0.833 ( \times 10^{23} )</td>
<td>1400</td>
<td>4.72 ± 0.10</td>
<td>142.9</td>
<td>0.34/0.43</td>
<td>3.40 ( \times 10^{-17} )</td>
</tr>
<tr>
<td>B:C</td>
<td>2.52</td>
<td>1.373 ( \times 10^{23} )</td>
<td>2723</td>
<td>4.26 ± 0.07</td>
<td>106.4</td>
<td>0.36/0.53</td>
<td>2.37 ( \times 10^{-17} )</td>
</tr>
<tr>
<td>BN</td>
<td>2.34</td>
<td>1.135 ( \times 10^{23} )</td>
<td>3000</td>
<td>4.87 ± 0.10</td>
<td>130.4</td>
<td>0.34/0.46</td>
<td>2.70 ( \times 10^{-17} )</td>
</tr>
</tbody>
</table>

### Table 1b. Characteristic parameters of interaction of ^7Li recoil nuclei produced during nuclear reaction (1.1) with energy \( E_{\text{Li}} = 1.01 \text{ MeV} \)

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>( \rho ) (( \text{g/cm}^3 ))</th>
<th>( N ) (( \text{atom/cm}^3 ))</th>
<th>( T_{\text{mel}} ) (K)</th>
<th>( R_{\text{Li}} ) (( \mu\text{m/Li} ))</th>
<th>( N_{\text{Li}}' ) (( \text{vac/Li} ))</th>
<th>( S_{\text{mel}}^\text{inel} ) (( \text{keV/Li} ))</th>
<th>( \sigma_{\text{mel}}^\text{inel} ) (( \text{dpa/cm}^2/Li ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>2.89</td>
<td>0.833 ( \times 10^{23} )</td>
<td>1400</td>
<td>2.13 ± 0.14</td>
<td>316.8</td>
<td>0.71</td>
<td>6.80 ( \times 10^{-17} )</td>
</tr>
<tr>
<td>B:C</td>
<td>2.52</td>
<td>1.373 ( \times 10^{23} )</td>
<td>2723</td>
<td>1.88 ± 0.07</td>
<td>244.4</td>
<td>0.79</td>
<td>5.60 ( \times 10^{-17} )</td>
</tr>
<tr>
<td>BN</td>
<td>2.34</td>
<td>1.135 ( \times 10^{23} )</td>
<td>3000</td>
<td>2.27 ± 0.10</td>
<td>292.7</td>
<td>0.91</td>
<td>5.85 ( \times 10^{-17} )</td>
</tr>
</tbody>
</table>
Peculiarities of neutron interaction with boron containing semiconductors

Table 2. Characteristics of neutron fluencies for different energies under irradiation of Fe77Ni2Si14B7 amorphous alloy [7]. \( \sigma_{\text{thermal}} \) is the approximate cross-section of damage creation for fast neutrons (at \( E_n > 0.1 \) MeV), \( \sigma_{\text{capture}} \) is the cross-section of thermal neutron capture by \(^{10}\)B atoms [2]

<table>
<thead>
<tr>
<th>Type of neutrons</th>
<th>( E_n ) (eV)</th>
<th>( \Phi_n ) (neutron/cm(^2))</th>
<th>( \sigma_{\text{fast}} ) (dpa ( \times ) cm(^2)/n)</th>
<th>( \sigma_{\text{thermal}} ) (barn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>0.01 ± 0.05</td>
<td>( \Phi_{\text{thermal}} = 2.1 \times 10^{17} )</td>
<td>no</td>
<td>3838 [9]</td>
</tr>
<tr>
<td>Resonance</td>
<td>0.45 ( \times ) 10(^3)</td>
<td>( \Phi_{\text{reson}} = 4.7 \times 10^{17} )</td>
<td>no</td>
<td>–</td>
</tr>
<tr>
<td>Fast</td>
<td>( 10^5 ) ( \pm ) ( 2 \times 10^7 )</td>
<td>( \Phi_{\text{fast}} = 1.8 \times 10^{17} )</td>
<td>( (2 \pm 4) \times 10^{-22} )</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 3. Calculated values of full numbers \( N_{\text{max}} \) and \( N_{\text{Li}} \) atoms in BP, B4C and BN semiconductors, numbers of produced \( \alpha \)-particles \( (N_{\alpha}) \) and \( ^7\)Li recoil nuclei \( (N_{\text{Li}}) \), damage doses \( D_n \) and \( D_{\text{Li}} \), full damage dose \( D_{\text{total}} = D_n + D_{\text{Li}} \) at a thermal neutron fluence of \( \Phi_{\text{thermal}} = 2.1 \times 10^n \) n/cm\(^2\), \( Z_{\text{max}} = 50 \) \( \mu \)m

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>( V_0 ) (0.005 cm(^3))</th>
<th>( N_{\text{Li}} ) at volume ( V = V_0 ) (cm(^3))</th>
<th>( \Phi_{\text{thermal}} ) (n/cm(^2))</th>
<th>( \sigma_{\text{capture}} ) (barn)</th>
<th>( N_{\alpha} ) and ( N_{\text{Li}} ) ( \times ) 10(^{16}) (dpa)</th>
<th>( D_n ) and ( D_{\text{Li}} ) ( \times ) 10(^{-2}) (dpa)</th>
<th>( D_{\text{total}} ) ( \times ) 10(^{-2}) (dpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>4.165 ( \times ) 10(^{20})</td>
<td>4.12 ( \times ) 10(^{19})</td>
<td>2.1 ( \times ) 10(^7)</td>
<td>3838</td>
<td>3.32</td>
<td>1.13/2.53</td>
<td>3.66</td>
</tr>
<tr>
<td>B4C</td>
<td>6.865 ( \times ) 10(^{21})</td>
<td>1.09 ( \times ) 10(^{20})</td>
<td>2.1 ( \times ) 10(^7)</td>
<td>3838</td>
<td>8.79</td>
<td>1.36/3.13</td>
<td>4.49</td>
</tr>
<tr>
<td>BN</td>
<td>5.675 ( \times ) 10(^{20})</td>
<td>5.62 ( \times ) 10(^{19})</td>
<td>2.1 ( \times ) 10(^7)</td>
<td>3838</td>
<td>4.53</td>
<td>1.04/2.33</td>
<td>3.37</td>
</tr>
</tbody>
</table>

(4) \( D_{\text{total}} = D_n + D_{\text{Li}} \)

The damage doses produced by \( \alpha \)-particles and by \( ^7\)Li recoil nuclei and full damage dose are presented in Table 3.

The value \( N_{\text{max}} \) in expression (3) is the full number of atoms in a thin layer of thickness \( Z_{\text{max}} = 50 \) \( \mu \)m of semiconductors sample.

As it is known, the concentration of light \( ^{10}\)B isotope atoms in natural elementary boron is 19.8%.

Damage dose under irradiation by fast neutrons of semiconductors (BN, BP and B4C) up to the fluence of \( \Phi_{\text{fast}} = 1.8 \times 10^{17} \) n/cm\(^2\) with approximate cross-section \( \sigma_{\text{fast}} \approx (2 \pm 4) \times 10^{-22} \) dpa \( \times \) cm\(^2\)/n should be:

(5) \( D_{\text{fast}} = \sigma_{\text{fast}} \times \Phi_{\text{fast}} \approx (3.6 \sim 7.2) \times 10^{-5} \) dpa

or less. Fast neutron fluence was taken from Ref. [7].

One can compare two values: \( D_{\text{E_{thermal}} > 2 \times 10^{-2}} \) dpa (see Table 3) and \( D_{\text{fast}} \approx (3.6 \sim 7.2) \times 10^{-5} \) dpa (5). It should be concluded that the damage creation in boron-contained semiconductors under irradiation with thermal neutrons takes place predominantly by means of fission fragments of nuclear reaction (1.1). Moreover, the radiation defects are distributed in the volume of semiconductors nearly uniformly. The corresponding calculations will be carried out below.

Calculations of damage depth distributions of thermal neutron absorption processes during passing through semiconductor flat-parallel samples with flight of fission fragments from lateral surfaces taken into account

During passage of thermal neutrons (in an energy range of 0.01 eV < \( E_n \) < \( E_n \text{ thermal} < 0.45 \) eV) through flat parallel samples of boron-containing semiconductors their flux should decrease under the capture process by \(^{10}\)B light isotope atoms (see nuclear reactions (1.1) and (1.2)). This process and the process of radioactive decay can be written by the differential equation:

(6) \( \frac{d\Phi_n(Z)}{dZ} = -\lambda_{\text{Z}} \times \Phi_n(Z) \)

One can obtain the dependence of the number of thermal neutrons on the depth \( Z \) from the left flat side of semiconductor samples, i.e. flux vs. the depth:

(7) \( \Phi_n^{\text{thermal}} (Z) = \Phi_n^{\text{thermal}} (0) \times \exp(-\lambda_{\text{Z}} \times Z) \), \( 0 \leq Z \leq Z_{\text{max}} \)

\( \lambda_{\text{Z}} \) is described by the equation:

(8) \( \lambda_{\text{Z}} = \sigma_{\text{capture}} \times \rho_{\text{B}^{10}} \)

where \( \rho_{\text{B}^{10}} \) is the number of \(^{10}\)B atom per cubic centimeter and \( \Phi_n^{\text{thermal}} (Z = 0) \) is the initial thermal neutron flux.

We suppose \( \Phi_n^{\text{thermal}} = 2.1 \times 10^{17} \) n/cm\(^2\) as in the case of irradiation in the fast neutron reactor IBR-2 [1, 2, 7, 15] of amorphous alloys using a pneumatic “post” of transportation channel “REGATA” [8]. Among boron-containing semiconductors, the maximum thermal neutron absorption should been in the case of B4C, where there are four boron atoms per each carbon atom. For this reason, we carried out all calculations for the small thickness \( Z_{\text{max}} = 50 \) \( \mu \)m. Let us introduce a new parameter using the expression:

(9) \( k_j = \frac{\Phi_n^{\text{thermal}} (Z = Z_j)}{\Phi_n^{\text{thermal}} (0)} \)

This parameter \( k_j \) is the attenuation parameter of neutron flux vs. the depth \( Z = Z_j \). The value of depth \( Z = Z_{\text{Li}} \) at \( k = 0.5 \) can be considered as the depth of the semi absorption. The depths \( Z_j \), whose corresponding values \( k_j \) can be written as:

(10) \( Z_j = -\frac{\ln(k_j)}{\sigma_{\text{capture}} \times \rho_{\text{B}^{10}}} \)

The depths \( Z_j \) for parameter \( k_j \approx 0.9; 0.7; 0.5; 0.3 \) and 0.1 are presented in Table 4 for three kinds of boron-containing semiconductor single crystals.

The densities of thermal neutrons after traveling through flat parallel samples with \( Z_{\text{max}} = 50 \) \( \mu \)m should be (see expression (7) and Table 4):

During passage of thermal neutrons (in an energy range of 0.01 eV < \( E_n \) < \( E_n \text{ thermal} < 0.45 \) eV) through flat parallel samples of boron-containing semiconductors their flux should decrease under the capture process by \(^{10}\)B light isotope atoms (see nuclear reactions (1.1) and (1.2)). This process and the process of radioactive decay can be written by the differential equation:
will take place of samples will be such that the following inequalities
scheme of such behavior is presented in Fig. 1.

Let us note that α-particles and 7Li recoil nuclei can escape from flat parallel surfaces of semiconductors if the captures of thermal neutrons by 10B atoms
(see nuclear reaction (1)) will take place near these parallel surfaces. In that case the flights of fission fragments should be in 4m geometry. The corresponding scheme of such behavior is presented in Fig. 1.

If the depths from both flat parallel lateral sides of samples will be such that the following inequalities will take place Z < Rα and Z < RLi (for the left side of samples) or Zmax − Rp < Z < Zmax and (for the right side of samples), respectively, and the direction of fission fragment flights will be to the surfaces then such fragments can leave sample and decrease the damage creation rate.

Table 4. Atomic density of 10B atoms (ρ010), parameters λZ (Eq. (7)), depths Z with coefficients k; for BP, B4C and BN. Thickness of all semiconductor samples Zmax = 50 μm, k = QOhmax(Z = Z)/QOhmax

<table>
<thead>
<tr>
<th>Type</th>
<th>ρ010 (atom/cm³)</th>
<th>λZ = σαmax/ρ010 (μm⁻¹)</th>
<th>Z₁ (μm)</th>
<th>Z₂ (μm)</th>
<th>Z₃ (μm)</th>
<th>Z₄ (μm)</th>
<th>Z₅ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>0.82 × 10⁻²</td>
<td>3.15 × 10⁻³</td>
<td>33</td>
<td>113</td>
<td>220</td>
<td>359</td>
<td>731</td>
</tr>
<tr>
<td>B₄C</td>
<td>2.17 × 10⁻²</td>
<td>8.33 × 10⁻³</td>
<td>13</td>
<td>43</td>
<td>83</td>
<td>136</td>
<td>276</td>
</tr>
<tr>
<td>BN</td>
<td>1.12 × 10⁻²</td>
<td>4.30 × 10⁻³</td>
<td>24</td>
<td>83</td>
<td>161</td>
<td>263</td>
<td>535</td>
</tr>
</tbody>
</table>

The percentage marked in round brackets was calculated under the assumption of initial neutron flux (11)

\[ \Phi_{10B} \] (Zmax = 50 μm) = 1.79 × 10⁻¹⁷ n/cm² (85%)\n
The corresponding calculations of damage distribution have been carried out in Ref. [7]. Here, we present the results of these calculations. The damage distribution dependence Dn,α,Z(Z) vs. the depth Z between the flat parallel surfaces of boron-containing semiconductors under the influence of elastic scattering of α-particles and 7Li recoil nuclei can be presented in the form:

\[ D_{n,α,li}^{total}(Z) = 0.5 × D_{α} \times \left[ 1 + \frac{Z}{R_{α}} \right] + 0.5 × D_{Li} \times \left[ 1 + \frac{Z}{R_{Li}} \right] \]

\[ \text{at } 0 ≤ Z ≤ R_{Li} \]

\[ D_{n,α,li}^{total}(Z) = D_{Li} + 0.5 × D_{α} \times \left[ 1 + \frac{Z}{R_{α}} \right] \]

\[ \text{at } R_{Li} ≤ Z ≤ R_{α} \]

\[ D_{n,α,li}^{total}(Z) = D_{α} + D_{Li} \times \left[ 1 + \frac{Z}{R_{α}} \right] \]

\[ \text{at } H − R_{α} ≤ Z ≤ H − R_{Li} \]

\[ D_{n,α,li}^{total}(Z) = 0.5 × D_{α} \times \left[ 1 + \frac{Z}{R_{α}} \right] + 0.5 × D_{Li} \times \left[ 1 + \frac{Z}{R_{Li}} \right] \]

\[ \text{at } H − R_{Li} ≤ Z ≤ H, \lambda_{Z} \subseteq [R_{Li}, 0] \]

Here, the parameters Rα,li = Rα + ΔRα,li, where Rα,li are the projected ranges and ΔRα,li are the half of widths of Bragg peaks for α-particles and 7Li recoil nuclei in boron containing semiconductors. This means that we take into account in our calculations only the particles that do not leave the samples irradiated by neutrons (0 ≤ Z ≤ Rli and H − Rα ≤ Z ≤ H).

For calculation of the whole damage, it is necessary to multiply the values of Dn,α,Z(Z), Eqs. (12), by thermal neutron absorption coefficients kabsorption = exp(−αZ × Z).

Then, we can write the final expression:

\[ D_{n,α,li}^{total}(Z) = D_{n,α,li}^{total}(Z) × \exp(−αZ × Z) \]

Relation (13) is an approximate one, because we did not take into account the correct integration of damage cross-section dependences vs. the depths and angles for some α-particles and 7Li recoil nuclei at boron containing semiconductors that left the samples.
The diffusion coefficient of electrically active impurities is proportional to point defect concentrations and equal [15, 17] to:

$$D_{\text{imp}} = \alpha \times \left[ d_{\text{imp},V} C_V + d_{\text{imp},I} C_I \right]$$

here \(\alpha\) is the thermodynamical factor, \(d_{\text{imp},V}\) and \(d_{\text{imp},I}\) are spatial diffusion coefficients in vacancies (\(V\)) and interstitial sites (\(I\)). \(C_V\) and \(C_I\) are vacancy and interstitial sites concentrations, respectively. So, creation of the point radiation defects by neutron leads to an increase of impurity diffusion.

As one can see, the total quantities of \(\alpha\)-particles and \(^{7}\text{Li}\) recoils at thermal neutron fluence \(\Phi_{n,\text{thermal}} = 2.1 \times 10^{17} \text{n/cm}^2\) are:

\[
\begin{align*}
N^{\text{Li}}(\text{BP}) &\approx 3.32 \times 10^{16}; \\
N^{\text{Li}}(\text{BN}) &\approx 4.53 \times 10^{16}; \\
N^{\text{Li}}(\text{B}_4\text{C}) &\approx 8.79 \times 10^{16}
\end{align*}
\]

in a relatively thick layer (volume is equal to \(V = 1 \text{ cm}^2 \times 0.005 \text{ cm}\), see Table 3). The average volume concentrations of \(^{7}\text{Li}\) atoms in all these semiconductors at this neutron fluence should be:

\[
\begin{align*}
n^{\text{Li}}(\text{BP}) &= 6.64 \times 10^{18} \text{ cm}^{-3}; \\
n^{\text{Li}}(\text{BN}) &= 9.06 \times 10^{18} \text{ cm}^{-3}; \\
n^{\text{Li}}(\text{B}_4\text{C}) &= 1.758 \times 10^{19} \text{ cm}^{-3}.
\end{align*}
\]

As it is well known, helium atoms are not electrically active, only \(^{7}\text{Li}\) impurities are electrically active in all the considered semiconductors. Let us calculate the volume concentrations of \(^{7}\text{Li}\) impurities vs. thermal neutron fluences. It is clear that the following dependences for average volume concentrations vs. thermal neutron fluences can be written:

\[
n^{\text{Li}}(\Phi_{n}) = \frac{n^{\text{Li}}(\Phi_{n,\text{thermal}})}{\Phi_{n,\text{thermal}}} \times \Phi_{n}
\]

Consequently, the absolute concentrations of \(^{7}\text{Li}\) impurities created after neutron transmutations can be changed very easy by variation of thermal neutron fluences. And also the damage dose of point defects (see Table 3) for the neutron fluence \(\Phi_{n,\text{thermal}} = 2.1 \times 10^{17} \text{n/cm}^2\) are equal to:

\[
\begin{align*}
D_{\text{total}}(\text{BP}) &\equiv 3.66 \times 10^{-2} \text{ dpa}; \\
D_{\text{total}}(\text{BN}) &\equiv 3.37 \times 10^{-2} \text{ dpa}; \\
D_{\text{total}}(\text{B}_4\text{C}) &\equiv 4.49 \times 10^{-2} \text{ dpa}.
\end{align*}
\]

A similar dependence of damage dose vs. thermal neutron fluences can be written as for the average concentrations [14].

Let consider some characteristics of BN, BP and B\(_4\)C semiconductors which we used for calculations in this article, these parameters are presented in Table 5. Top symbols '*' and '**' for BP semiconductor mean a single crystal or a thin film [9], respectively. Top symbol '+' for B\(_{4}\)C\(_{ab}\) semiconductor corresponds to a polycrystalline material and type of carriers not determined [9].

One can conclude using the comparison of calculated values of \(^{7}\text{Li}\) atom average concentrations in the
considered semiconductors and its carrier concentrations, that at this thermal neutron fluences such values are very close.

It is necessary to note that, as a rule, lithium atoms have very big mobility (high diffusivity) at room temperatures too and try to be absorbed by the surface layers of materials. This is the reason why it is necessary to keep germanium semiconductor detectors at liquid nitrogen temperature and why there exist the so-called sweating alloys with high concentration of lithium atoms. So, it is necessary to study the diffusivity of lithium in all the discussed semiconductors because Li can leave bulk semiconductors and may be absorbed by their surfaces.

Table 5. Some characteristic parameters of BN, BP and B,C semiconductors [6, 9]

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Density, g/cm$^3$</td>
<td>3.487</td>
<td>2.89</td>
<td>2.52</td>
</tr>
<tr>
<td>Lattice parameter, nm</td>
<td>0.36157</td>
<td>0.4538</td>
<td>0.56(a); 1.212(c)</td>
</tr>
<tr>
<td>Energy gap, eV</td>
<td>5.8$\pm$6.2</td>
<td>2.0</td>
<td>1.64</td>
</tr>
<tr>
<td>Melting point, K</td>
<td>3246</td>
<td>1400</td>
<td>2723</td>
</tr>
<tr>
<td>Carrier concentration, cm$^{-3}$</td>
<td>$n^\text{p}$</td>
<td>$10^{18} (500 \text{ K})^\text{p}$</td>
<td>$7 \times 10^{16} + 4 \times 10^{19} (300 \text{ K})$</td>
</tr>
<tr>
<td></td>
<td>$p^\text{p}$</td>
<td>$10^{17} (900 \text{ K})^\text{p}$</td>
<td>$8 \times 10^{17} + 2 \times 10^{19} (300 \text{ K})$</td>
</tr>
</tbody>
</table>

The variation of thermal neutron fluence allows one to change the active $^7\text{Li}$ impurity and vacancy concentrations and the vacancies in all the considered semiconductors in wide value intervals at a relatively low level of neutron fluences (see expression (16)).

References