Macroscopic description of the diffusion of interstitial impurity atoms considering the influence of elastic stress on the drift of interstitial species

O. I. Velichko

Department of Physics, Belarusian State University of Informatics and Radioelectronics, 6, P. Brovka Street, Minsk, 220013 Belarus, E-mail: oleg_velichko@lycos.com

Abstract

The diffusion equation for nonequilibrium interstitial impurity atoms taking into account their charge states and drift of all mobile interstitial species in the built-in electric field and in the field of elastic stress was obtained. The obtained generalized equation is equivalent to the set of diffusion equations written for the interstitial impurity atoms in each individual charge state. Due to a number of the characteristic features the generalized equation is more convenient for numerical solution than the original system of separate diffusion equations.

On this basis, the macroscopic description of stress-mediated impurity diffusion due to a kick-out mechanism was obtained. It is supposed that the interstitial impurity atom makes a number of jumps before conversion to the substitutional position. At the same time, a local equilibrium prevails between substitutionally dissolved impurity atoms, nonequilibrium self-interstitials, and interstitial impurity atoms. Also, the derived equation for impurity diffusion due to the kick-out mechanism takes into account all charge states of interstitial impurity atoms as well as drift of interstitial species in the electric field and in the field of elastic stress. Moreover, this equation exactly matches the equation of stress-mediated impurity diffusion due to generation, migration, and dissociation of the equilibrium pairs “impurity atom – self-interstitial”.

Keywords: Theory of diffusion; diffusion; exchange interactions; annealing; semiconductors
1 Introduction

In recent years a mechanism of dopant diffusion in silicon due to formation, migration and dissociation of the pairs “impurity atom – vacancy” or “impurity atom – self-interstitial” (pair diffusion mechanism) has become commonly accepted (see, for example [1, 2, 3]). However, boron diffusion in silicon is often considered within the framework of the substitutional-interstitial mechanism [4, 5, 6] when the silicon self-interstitial displaces an immobile impurity atom from substitutional to the interstitial position. A migrating interstitial impurity atom in turn replaces the host atom becoming substitutional again (so-called “kick-out mechanism”).

It is supposed that kick-out mechanism is also responsible for the diffusion of gold in silicon [7, 8]; zinc [9, 10, 11, 12, 13, 14, 15, 16], nitrogen [17, 18, 19], magnesium [20, 21, 22, 23], and beryllium [11, 14, 20, 23] in GaAs. As follows from the data of investigations [14, 24, 25], beryllium diffusion in other compound semiconductors is governed by kick-out mechanism too.

A number of diffusion equations were proposed [1, 4, 7, 10, 11, 13, 14, 16, 19, 22, 23, 24, 25, 26] to describe migration of interstitial impurity atoms. The equations used in [4, 7, 10, 19] do not take into account the electric field effect on the migration of interstitial impurity atoms and can be used only for modeling of the diffusion of neutral interstitial species. The influence of built-in electric field on the drift of charged impurity interstitials is taken into consideration in [1, 11, 14, 16, 24, 25], but diffusion equations were obtained only for the case of a single charge state of impurity interstitials. The general case of diffusion of impurity interstitial atoms in different charge states was considered in [13, 22, 23, 26]. In these papers the equations for diffusion of impurity interstitials and impurity diffusion due to kick-out mechanism were obtained. The sum operation of diffusion equations for impurity interstitials in different charge states, the mass action law for conversions between different charge states of diffusing species, and the mass action law for the conversion reactions of impurity atoms between substitutional and interstitial sites were used in [13, 22, 23] to obtain the diffusion equation for impurity interstitials. In contrast to [13, 22, 23], in paper [26] the mass action law for conversions between different charge states of diffusing species was used to obtain the diffusion equation in which only the concentration of neutral
impurity interstitials $C^{AI\times}$ is included. This equation has the form

$$\frac{\partial \left( \xi^{AI} C^{AI\times} \right)}{\partial t} = \nabla \left[ D^{AI} \nabla C^{AI\times} \right] - \left( k^{AI} + k^{AV} \tilde{C}^{V\times} \right) C^{AI\times} + k^W \tilde{C}^{I\times} C + G^{ACI} - S^{ACI} + G^{ARI} - S^{ARI},$$

(1)

$$\xi^{AI}(\chi) = \sum_k h^{AIk}_i \chi^{-zz^k}_k,$$

(2)

$$D^{AI}(\chi) = \sum_k D^{AIk} h^{AIk}_i \chi^{-zz^{AIk}_k},$$

(3)

$$k^{AI}(\chi) = \sum_k k^{AIk} h^{AIk}_i \chi^{-zz^{AIk}_k},$$

(4)

$$k^{AV}(\chi) = \sum_k k^{AVk} h^{AIk}_i \chi^{-zz^{AIk}_k},$$

(5)

$$k^W(\chi) = \sum_k k^Wk h^{AIk}_i \chi^{-zz^{AIk}_k},$$

(6)

$$\tilde{C}^{I\times} = \frac{C^{I\times}}{C^{I\times}_i}, \quad \tilde{C}^{V\times} = \frac{C^{V\times}}{C^{V\times}_i},$$

(7)

$$S^{ACI} = \sum_k S^{ACIk}, \quad G^{ACI} = \sum_k G^{ACIk},$$

(8)

$$S^{ARI} = \sum_k S^{ARIk}, \quad G^{ARI} = \sum_k G^{ARIk},$$

(9)

where $D^{AI}(\chi)$ is the effective diffusivity of interstitial impurity atoms; $\chi$ is the concentration of charge carriers (electrons or holes) normalized to the intrinsic carrier concentration $n_i$; $k^{AI}(\chi)$ is the effective coefficient of absorption of interstitial impurity atoms due to kick-out of host atoms from the lattice sites; $k^{AV}(\chi)$ is the effective coefficient describing absorption of interstitial impurity atoms due to their interaction with vacancies (can be used for simulation of Frank-Turnbull diffusion mechanism [27]); $k^W(\chi)$ is the effective coefficient describing generation of interstitial impurity atoms due to replacement of the impurity by self-interstitials from the substitutional position to the interstitial one (Watkins effect [28]); $h^{AIk}_i$ are the constants of the
local equilibrium for conversions between different charge states of impurity interstitials; \( k \) is the charge state of interstitial impurity atom \( A_I^k \); \( z \) and \( z^{AIk} \) are respectively the charges of impurity atom in substitutional and interstitial positions in terms of the elementary charge (\( z = +1 \) in the case of doping by donors and \( z = -1 \) for an acceptor impurity); \( C^{I\times} \) and \( C_{i\times}^{I} \) are the actual and equilibrium concentrations of self-interstitials in the neutral charge state; \( C^{V\times} \) and \( C_{i\times}^{V} \) are the actual and equilibrium concentrations of vacancies in the neutral charge state; \( S_{ACI} \) and \( G_{ACI} \) are respectively the effective rates of absorption and generation of impurity interstitials during the formation (annealing) of the clusters of impurity atoms; \( S_{ARI} \) and \( G_{ARI} \) are respectively the effective rates of absorption and generation of impurity interstitial atoms due to evolution of radiation defects. As can be seen from the expressions (3, 4, 5, 6) and (8, 9), the effective coefficients and effective functions are obtained by sum operation of analogous quantities for each individual charge state \( k \).

Eq.(1) has the following characteristic features. i) In comparison with the equations of [13, 22, 23], the obtained equation can describe long-range migration of nonequilibrium impurity interstitials because the mass action law for substitutional impurity, self-interstitials, and impurity interstitial atoms was not used. ii) This equation describes diffusion of all interstitial impurity atoms with different charge states as a whole, although only the concentration of the neutral impurity interstitials \( C^{AI\times} \) must be obtained to solve the equation. iii) The obtained equation takes into account the drift of all charged species due to the built-in electric field. At the same time, there is no explicit term describing the drift.

It is to be noted that Eq.(1) is very convenient for numerical solution owing to the features ii) and iii). However, similar to the equations of [13, 22, 23], Eq.(1) ignores the drift of impurity interstitials in the field of elastic stresses. But the available experimental data show that elastic stresses can significantly influence the impurity diffusion [29, 30, 31], including the case of Be diffusion in p+ GaAs [29]. Thus, the macroscopic description of stress-mediated diffusion of interstitial impurity atoms requires further investigations.

Yoshida et. al. [32] have investigated qualitatively the changes in the lattice configurations of impurity atom and self-interstitial in silicon for kick-out and pair diffusion mechanisms and concluded that there is no essential difference between the macroscopic descriptions of both mechanisms of impurity migration. However, a rigorous proof of this statement has not been
given. Moreover, in [32] the charge states of impurity atoms and point defects were not considered, and the drift of charged particles in the built-in electric field was not taken into account. It was mentioned in [6, 22, 33, 34] that the pair diffusion model is mathematically equivalent to the kick-out mechanism, but only in [22] the equation for impurity diffusion obtained for kick-out mechanism was compared with the diffusion equation for the pair diffusion mechanism. In all these papers the case of stress-mediated diffusion was not considered. Besides, it was supposed in [22] that a local equilibrium between substitutionally dissolved impurity atoms, self-interstitials, and impurity interstitial atoms prevails. This condition is easily implemented if the generated impurity interstitial atom makes only one jump before conversion to the substitutional position. But in this case the jump direction is dependent on the gradient of self-interstitial concentration. It is supposed for the pair diffusion mechanism that the pairs make a number of jumps before their dissociation. The plain fact is that the direction of the pair migration is independent of the gradient of self-interstitial concentration. The diffusion equations for both mechanisms will be different if the impurity interstitial atom makes only one jump while the distribution of self-interstitials is not uniform. Therefore, it seems reasonable to verify the identity of the macroscopic descriptions for the pair and kick-out diffusion mechanisms if the stress-mediated migration occurs.

The purpose of this study is to obtain the equation of the diffusion of interstitial impurity atoms taking into account all their charge states and drift of all interstitial species in the built-in electric field as well as in the field of elastic stresses. On this basis, the identity of the macroscopic descriptions of both diffusion mechanisms for stress-mediated diffusion can be confirmed.

2 Diffusion equation for nonequilibrium interstitial impurity atoms

Taking into consideration the charge states of impurity atoms and self-interstitials, the reaction for kick-out mechanism can be written in the form similar to that used in [4, 5, 6, 22]

\[ A_S + I^q + m_e e^- \rightleftharpoons A_I^k, \]  

(10)
where $A_S$ and $A_I^k$ are the impurity atoms in substitutional and interstitial positions, respectively; $I^q$ is the self-interstitial in the charge state $q$; $m_e$ is the number of electrons participating in the reaction.

It is important to note that the charge conservation law

$$z + z^q - m_e = z^k$$

(11)

is valid for reaction (10). Here $z^q$ is the charge of a self-interstitial.

Let us suppose that an interstitial impurity atom makes a number of jumps before conversion to the substitutional position, i.e. migration of interstitial impurity species in the absence of electric and stress fields is chaotic. Then, the influence of cross-effects [35] is negligible, and the diffusion equation of the interstitial impurity atoms with the charge state $k$ can be written in the following form:

$$\frac{\partial C^{AIk}}{\partial t} = \frac{\partial}{\partial x}\left(D^{AIk} \frac{\partial C^{AIk}}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{z z^{AIk} D^{AIk} C^{AIk}}{\chi} \frac{\partial \chi}{\partial x}\right) +$$

$$\frac{\partial}{\partial x}\left(\frac{D^{AIk} C^{AIk}}{k_B T} \frac{\partial U^{AIk}}{\partial x}\right) - S^{AIk} + G^{AIk},$$

(12)

where $C^{AIk}$ and $D^{AIk}$ are the concentration and diffusivity of interstitial impurity atoms in the charge state $k$, respectively; $U^{AIk}$ is the potential energy of the interstitial impurity atom in the charge state $k$ in the field of elastic stress; $S^{AIk}$ and $G^{AIk}$ are respectively the absorption and generation rates of the interstitial impurity atoms in the charge state $k$ per unit volume of semiconductor.

The terms in brackets in the right-hand side of Eq.(12), taken with the minus sign, describe the fluxes of impurity interstitials due to the concentration gradient, drift in the built-in electric field, and drift under the influence of elastic stress, respectively.

Let us assume that interstitial impurity atoms have different charge states including the neutral one. In this case a system of equations (12) written for all charge states $k$ should be used for description of the impurity interstitial diffusion.

The conversions of interstitial impurity atoms between different charge states are described by the following reactions:

$$A^x - z^{AIk}e^- \leftrightarrow A^{AIk}.$$  

(13)
Due to high mobility of electrons (holes) there is a local thermodynamic equilibrium between the interstitials in different charge states and electrons (holes). Then, for reaction (13) the relation
\[ \frac{C^{AIk}}{C^{AI\times} \chi^{-z} z^{AIk}} = h^{AIk}, \] (14)
can be obtained from the mass action law. Here \( h^{AIk} \) is the constant of a local thermodynamic equilibrium for this reaction.

Substituting the concentration of impurity interstitials \( C^{AIk} \) from the relation (14) in Eq. (12), we transform this equation to the following form:
\begin{align*}
\frac{\partial}{\partial t} \left( \frac{C^{AIk}}{C^{AI\times} \chi^{-z} z^{AIk}} a^{AIk} C^{AI\times} \right) &= \frac{\partial}{\partial x} \left[ D^{AIk} h_i^{AIk} \frac{\chi^{-z} z^{AIk}}{k_B T} \frac{\partial U^{AIk}}{\partial x} \right] + \\
&- \sum_k \frac{D^{AIk} h_i^{AIk} \chi^{-z} z^{AIk}}{k_B T} \frac{\partial U^{AIk}}{\partial x} + S^{AIk} + G^{AIk},
\end{align*}
(15)
where the functions \( a^{AIk} = \frac{h^{AIk}}{h_i^{AIk}} \) describe deviation of the constants of a local thermodynamic equilibrium in the heavily doped region \( h^{AIk} \) from their intrinsic values in the undoped semiconductor \( h_i^{AIk} \).

Let us assume that the functions \( a^{AIk} \) depend weakly on the charge state of impurity interstitial, i.e. \( a^{AIk} \approx a^{AI} \) holds. Then, summing the equations (15) written for different charge states \( k \), one can obtain the generalized diffusion equation for nonequilibrium interstitial impurity atoms
\begin{align*}
\frac{\partial}{\partial t} \left[ \xi^{AI} (\chi) a^{AI} C^{AI\times} \right] &= \frac{\partial}{\partial x} \left[ \frac{D^{AI} (\chi)}{D^{AI\times}} \frac{\partial (a^{AI} C^{AI\times})}{\partial x} \right] - \\
&- \sum_k \frac{D^{AIk} h_i^{AIk} \chi^{-z} z^{AIk}}{k_B T} \frac{\partial U^{AIk}}{\partial x} + S^{AI} + G^{AI},
\end{align*}
(16)
\[ v^{AI} (x, \chi) = -\sum_k \frac{D^{AIk} h_i^{AIk} \chi^{-z} z^{AIk}}{k_B T} \frac{\partial U^{AIk}}{\partial x}, \] (17)
In Eq. (16) quantities $D^{A_I}(\chi)$ and $v^{A_I}(x, \chi)$ are the effective diffusivity of interstitial impurity atoms and effective drift velocity of impurity interstitials in the field of elastic stress, respectively. Note that the expressions (2) and (3) are valid for the quantities $\xi^{A_I}(\chi)$ and $D^{A_I}(\chi)$.

Similar to Eq. (1), the obtained diffusion equation (16) is characterized by the following features. i) This equation can describe the long-range migration of nonequilibrium impurity interstitials. ii) This equation describes diffusion of all the interstitial impurity atoms with different charge states as a whole, that is a set of equations (12) is replaced by one generalized diffusion equation (16). iii) The only variable that should be estimated in this equation is the concentration of neutral impurity interstitials. iv) The obtained equation takes into account the drift of charged species due to the built-in electric field. However, there is no explicit term describing the drift due to the electric field. v) Although the effective coefficients of Eq. (16) represent nonlinear functions of $\chi$ in comparison with the constant transport coefficients of equations (12), these functions are smooth and monotone. vi) Eq. (16) describes in general diffusion of the nonequilibrium interstitial impurity atoms regardless of the mechanism of interstitial generation.

Note that due to the above-mentioned features, Eq. (16) is more convenient for numerical solution than a set of equations (12).

3 Diffusion equation for interstitial impurity atoms under equilibrium conditions

Now, on the basis of Eq. (16), the interstitial diffusion due to a kick-out mechanism can be investigated. Within the framework of the kick-out mechanism the impurity interstitial is generated as a result of interaction between the substitutionally dissolved impurity atom and self-interstitial via the reaction (10) or due to generation of the interstitial impurity atom in the neutral charge state via the reaction

$$A_S + I^+ + m^{A_{I^+}} e^- \leftrightarrow A_{I^+}^x,$$

where $A_{I^+}^x$ and $I^x$ are the interstitial impurity atom and self-interstitial in the neutral charge states, respectively; $m^{A_{I^+}}$ is the number of electrons participating in the reaction (18), where from the charge conservation law it follows that $m^{A_{I^+}} = z$. 

8
Usually, it is assumed that there is a local thermodynamic equilibrium between substitutionally dissolved impurity atoms, self-interstitials, and impurity atoms in the interstitial position. Then, for reaction (18) the mass action law can be written in the form

\[
\frac{C^{AI\times}}{C^{I\times}} \chi^z m^{AI\times} = H^{AI\times},
\]

where \( C \) is the concentration of substitutionally dissolved impurity atoms; \( C^{I\times} \) is the concentration of self-interstitials in the neutral charge state \( I^\times \); \( H^{AI\times} \) is the constant of a local thermodynamic equilibrium for reaction (18).

With \( m^{AI\times} = z \) relation (19) may be as follows:

\[
C^{AI\times} = H^{AI\times} \chi C^{I\times}.
\]

Substitution of (20) into (16) gives the generalized diffusion equation of interstitial impurity atoms in the following form:

\[
\frac{\partial}{\partial t} \left[ \xi(\chi) a \tilde{C}^{I\times} \right] = \frac{\partial}{\partial x} \left[ D(\chi) \frac{\partial}{\partial x} \left( a \tilde{C}^{I\times} \right) + D(\chi) \frac{a \tilde{C}^{I\times} \partial \chi}{\chi} \right] - \frac{\partial}{\partial x} \left[ v(x, \chi) a \tilde{C}^{I\times} \right] - S^{AI} + G^{AI},
\]

\[
\xi(\chi) = \xi^{AI}(\chi) H^{AI\times}_i C^{I\times}_i \chi = H^{AI\times}_i C^{I\times}_i \sum_k h^{AI}_{ik} \chi^{-z} z^{AIk} + 1,
\]

\[
a = \frac{H^{AI\times}_i h^{AI\times}_i}{H^{AI\times}_i h^{AI\times}_i},
\]

\[
D(\chi) = D^{AI}(\chi) H^{AI\times}_i C^{I\times}_i \chi =
\]

\[
H^{AI\times}_i C^{I\times}_i \sum_k D^{AIk} h^{AIk} \chi^{-z} z^{AIk} + 1,
\]

\[
v(x, \chi) = v^{AI}(x, \chi) H^{AI\times}_i C^{I\times}_i \chi =
\]

\[
- \frac{H^{AI\times}_i C^{I\times}_i}{k_B T} \sum_k D^{AIk} h^{AIk} \partial U^{AIk}/\partial x \chi^{-z} z^{AIk} + 1.
\]
Eq. (21) is not so general as Eq. (16), because it gives no description for the long-range migration of the nonequilibrium impurity interstitials. On the other hand, Eq. (21) is valid for the very important case of the local equilibrium between substitutionally dissolved impurity atoms, self-interstitials, and impurity atoms in the interstitial position. The concentration of interstitial impurity atoms is not included in the explicit form in Eq. (21), although diffusion occurs due to migration of interstitial impurity species in different charge states.

4 Equation of impurity diffusion due to kick-out mechanism

Based on Eq. (21), we can obtain the equation of impurity diffusion due to a kick-out mechanism. It is commonly accepted that the substitutionally dissolved impurity atoms are immobile. Then, the conservation law for substitutional impurity atoms can be written in the form

$$\frac{\partial C}{\partial t} = S^{AI} - G^{AI}. \quad (26)$$

Combining Eq. (21) and Eq. (26) and taking into account that the concentration of interstitial impurity atoms is essentially smaller than the concentration of substitutionally dissolved impurity atoms gives the final equation of impurity diffusion due to a kick-out mechanism

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left\{ D(\chi) \left[ \frac{\partial (a \tilde{C}^{I\times C})}{\partial x} + a \tilde{C}^{I\times C} \frac{\partial \chi}{\partial x} \right] \right\} - \frac{\partial}{\partial x} \left[ v(x, \chi) a \tilde{C}^{I\times C} \right]. \quad (27)$$

As can be seen from Eq. (27), the concentration of interstitial impurity atoms is not included in the explicit form in this equation, although Eq. (27) describes the diffusion due to a kick-out mechanism. The effective coefficients $D(\chi)$ and $v(x, \chi)$ of Eq. (27) are the same as in Eq. (21), i.e. they represent smooth and monotone functions of $\chi$. Moreover, the obtained equation Eq. (27) exactly matches the equation of impurity diffusion due to generation, migration, and dissociation of the equilibrium pairs "impurity atom –
self-interstitial”, where the influence of elastic stress on the drift of the pairs is taken into account [36, 37]. Thus, we can confirm the conclusion of [22] that macroscopic descriptions of impurity diffusion due to the kick-out and pair diffusion mechanisms are the same and analysis of the impurity concentration profiles does not allow to choose between these diffusion mechanisms. In our opinion, the difference can arise only in the case when the interstitial impurity atom makes one jump before conversion to the substitutional position. Because of this, it is possible to use a wide-spread software based on the models of pair diffusion for simulation of the diffusion processes due to a kick-out mechanism even if a stress-mediated migration occurs.

5 Conclusions

The diffusion equation for nonequilibrium interstitial impurity atoms, taking into account their different charge states and drift of all mobile interstitial species in the built-in electric field and in the field of elastic stresses, was obtained. The obtained generalized equation has the following characteristic features. i) This equation can describe the long-range migration of nonequilibrium impurity interstitials. ii) A set of diffusion equations written for the interstitial impurity atoms in each individual charge state is replaced by a single generalized equation. iii) The concentration of neutral impurity interstitials is the only variable that should be estimated in the obtained equation. iv) There is no explicit term describing the drift due to electric field in the equation obtained. v) Although the effective coefficients of the diffusion equation for interstitial impurity atoms represent nonlinear functions of the concentration of charged carriers, these functions are smooth and monotone. Due to these features, the derived equation is convenient for numerical solution.

Based on the obtained generalized equation and mass action law for the interstitial impurity atoms being in equilibrium with substitutionally dissolved impurity and self-Interstitials, the equation of impurity diffusion due to a kick-out mechanism was derived. The obtained equation of impurity diffusion takes into account all charge states of interstitial impurity atoms and drift of interstitial species in the electric field and in the field of elastic stresses. The effective coefficients of this diffusion equation also represent smooth and monotone functions of the charge carrier concentration. Moreover, the obtained equation exactly matches the equation of impurity diffu-
sion due to generation, migration, and dissociation of the equilibrium pairs “impurity atom – self-interstitial”, where the influence of elastic stresses on the drift of the pairs is taken into account. Thus, the conclusion of [22] concerning identity of the governing diffusion equations for both diffusion mechanisms is extended to the case of stress-mediated diffusion.

References

[1] O. I. Velichko, in: I. I. Danilovich, A. G. Koval’, V. A. Labunov et al. (Eds.), Proceedings of VII International Conference “Vzaimodeistvie Atomnyh Chastits s Tverdym Telom (Interaction of Atomic Particles with Solid)”, Part 2, Minsk (Belarus), 1984, pp.180-181 [In Russian].

[2] D. Mathiot, S. Martin, J. Appl. Phys. 70 (1991) 3071-3080.

[3] TSUPREM—4 User’s Manual. Version 2000.4, Avant! Corp., Fre- mont CA, 2000.

[4] M. Uematsu, J. Appl. Phys. 82 (1997) 2228-2246.

[5] L. Ihaddadene-Le Coq, J. Marcon, A. Dush-Nicolini, K. Masmoudi, K. Ketata, Nucl. Instrum. Methods Phys. Res., Sect. B 216 (2004) 303-307.

[6] I. Martin-Bragado, R. Pinacho, P. Castrillo, M. Jaraiz, J.E. Rubio, J. Barbolla, Mater. Sci. Eng., B 114-115 (2004) 284-289.

[7] U. Gösele, W. Frank, A. Seeger, Appl. Phys. 23 (1980) 361-368.

[8] A. Seeger, Phys. Status Solidi A 61 (1980) 521-629.

[9] U. Gösele, F. Morehead, J. Appl. Phys. 52 (1981) 4617-4619.

[10] S. Reynolds, D. W. Vook, J. F. Gibbons, J. Appl. Phys. 63 (1988) 1052-1059.

[11] S. Yu, T. Y. Tan, U. Gösele, J. Appl. Phys. 69 (1991) 3547-3565.

[12] G. Bösker, N. A. Stolwijk, H.-G. Hettwer, A. Rucki, W. Jäger, U. Södervall, Phys. Rev. B 52 (1995) 11927-11931.
[13] M. P. Chase, M. D. Deal, J. D. Plummer, J. Appl. Phys. 81 (1997) 1670-1676.

[14] C.-H. Chen, U. M. Gosele, T. Y. Tan, Appl. Phys. A 68 (1999) 9-18.

[15] H. Bracht, M. S. Norseng, E. E. Haller, K. Eberl, Physica B 308-310 (2001) 831-834.

[16] H. Bracht, S. Brotzmann, Phys. Rev. B 71 (2005) 115216-1 - 115216-10.

[17] G. Bösker, N. A. Stolwijk, J. V. Thordson, U. Södervall, T. G. Andersson, Phys. Rev. Lett. 81 (1998) 3443-3446.

[18] N. A. Stolwijk, G. Bösker, J. V. Thordson, U. Södervall, T. G. Andersson, Ch. Jäger, W. Jäger, Physica B 273-274 (1999) 685-688.

[19] N. A. Stolwijk, G. Bösker, T. G. Andersson, U. Södervall, Physica B 340-342 (2003) 367-370.

[20] H. G. Robinson, M. D. Deal, D. A. Stevenson, Appl. Phys. Lett. 56 (1990) 554-556.

[21] H. G. Robinson, M. D. Deal, D. A. Stevenson, Appl. Phys. Lett. 58 (1991) 2800-2802.

[22] H. D. Robinson, M. D. Deal, G. Amaratunga, P. B. Griffin, D. A. Stevenson, J. D. Plummer, J. Appl. Phys. 71 (1992) 2615-2623.

[23] J. C. Hu, M. D. Deal, J. D. Plummer, J. Appl. Phys. 78 (1995) 1595-1605.

[24] K. Ketata, M. Ketata, S. Koumetz, J. Marcon, O. Valet, Physica B 273-274 (1999) 823-826.

[25] M. Ihaddadene-Lenglet, J. Marcon, Nucl. Instrum. Methods Phys. Res., Sect. B 216 (2004) 297-302.

[26] O. I. Velichko, Simulation of coupled diffusion of impurity atoms and intrinsic point defects in semiconductor crystals, D.Sc. thesis, Belarusian State University, 1996 [In Russian].
[27] F. C. Frank, D. Turnbull, Phys. Rev. 104 (1956) 617-618.

[28] G. D. Watkins, IEEE Trans. NS-16 (1969) 13-18.

[29] Biing-Der Liu, Tung-Ho Shieh, Meng-Yueh Wu, Si-Chen Lee, Hao-Hsiung Lin, J. Appl. Phys. 72 (1992) 2767-2772.

[30] Y. S. Lim and J. Y. Lee, H. S. Kim, D. W. Moon, Appl. Phys. Lett. 77 (2000) 4157-4159.

[31] M. J. Aziz, Mater. Sci. Semicond. Process. 4 (2001) 397-403.

[32] M. Yoshida, Y. Kamiura, R. Tsuruno, M. Takahashi, H. Tomokage, Jpn. J. Appl. Phys., Part 1 37 (1998) 6376-6377.

[33] M. Yoshida, E. Arai, Jpn. J. Appl. Phys., Part 1 34 (1995) 5891-5903.

[34] M. Uematsu, Jpn. J. Appl. Phys., Part 1 36 (1997) 7100-7103.

[35] E. C. Aifantis, Acta Metall. 27 (1979) 683-691.

[36] O. I. Velichko, A. K. Fedotov, Solid State Phenomena, 57-58 (1997) 513-518.

[37] A. K. Fedotov, O. I. Velichko, V. A. Dobrushkin, J. Alloys Compd. 382 (2004) 283-287.