

# Grain Boundary Diffusion Patterns under Nonequilibrium and Migration of Grain Boundaries in Nanostructure Materials\*

V. V. Krasil'nikov, S. E. Savotchenko

*Belgorod State University*

*e-mail: kras@bsu.edu.ru*

**Abstract**—In this work, the model of grain boundary diffusion from a permanent source along nonequilibrium migratory grain boundaries is considered. Grain boundary nonequilibrium is characterized by a value of boundary excess energy up to which relaxation goes. It is shown increasing excess energy and migration velocity of nonequilibrium boundaries lead to increasing diffusant volume penetrating into a sample during annealing time.

## INTRODUCTION

A number of investigations have shown that grain boundary diffusion coefficient is determined by a grain boundary structure but not only an average grain size [1]. In [2], it is pointed out that diffusion coefficient depends on time in a real diffusion nanocrystal experiment. This affects its value measured experimentally. The dependence of diffusion coefficient on time is due to grain boundaries are in a nonequilibrium state in samples prepared shortly before some of experiments. In [3–5], it is shown that nonequilibrium of the grain boundaries conditions the dependence of grain boundary diffusion coefficient on a boundary excess volume changed by a mass transfer process.

As shown [6], the grain boundary can migrate during diffusion, for instance, in time of recrystallization, broken precipitation and so on. Influence of grain boundary migration at constant diffusion coefficient on distribution of diffusant concentration has been analyzed in [7] under diffusion from a permanent source. It is clear that the migrant boundaries in nanocrystals can be unsteady involving necessity of allowing for the dependence of diffusion coefficient on time in constructing models of grain boundary diffusion.

In the present work, it is analyzed the time dependence of diffusion coefficient, conditioned by nonequilibrium of the grain boundaries, and distribution of diffusant concentration in migrating the grain boundaries.

## *Model of Grain Boundary Diffusion Along Nonequilibrium Migrating Grain Boundaries from Source at Constant Concentration*

We consider the generalization of grain boundary diffusion models proposed in [2, 7]. Let the grain boundary is a uniform rectangular plate of the  $\delta$  thickness, located in a half-infinite sample. Upon that the boundary plane is perpendicular to a nanocrystal surface (plane  $yOz$ ) coated by diffusant. It is also assumed that the boundary parallel to the plane  $xOy$  moves with constant velocity  $V$  along the normal to its surface, i.e. along the axis  $Oz$ . In addition, it is assumed that any point in a crystal intersects only one migrant boundary (similar to the model of isolated fixed boundaries [7]). This assumption means that the distance between grain boundaries  $d_g$  is essentially more than displacement boundary. In this case, the concentration at the crystal where the migrant boundary wanders in the current time  $t$  is equal to the instantaneous concentration  $c(x, t)$  in the grain boundaries at the moment when the boundary bypasses this point. Also, it is assumed that diffusion goes in  $C$  regime, i.e. when the bulk diffusion significantly smaller than the grain one. In this case diffusant can go only to the crystal points which intersect the moving boundary. When impurities diffuse segregation can lead to the fact that only part of diffusant remains in the rear of migrant boundary.

The equation that describes the distribution of diffusant concentration  $c(x, t)$  following [7] can be written as:

$$\frac{\partial c}{\partial t} = D(t) \frac{\partial^2 c}{\partial x^2} - \frac{V}{\delta} c, \quad x > 0, \quad t > 0, \quad (1)$$

where  $D(t)$  is nonequilibrium grain diffusion coefficient.

\*The article was translated by the author.

It is considered that the initial sample does not contain diffusant. This is expressed in terms of initial conditions:

$$c(x, 0) = 0, \quad x > 0. \quad (2)$$

When considering the process of diffusion from surface sources of  $c_s$  concentration it should be used the boundary condition of the 1st kind:

$$c(0, t) = c_s(t), \quad t > 0. \quad (3)$$

Thus, the mathematical definition of the assumptions formulated above reduces to the first initial-boundary problem on the semi-axis. The solution of this problem (1)–(3) for an arbitrary dependence of diffusion coefficient on time can be written as:

$$c(x, t) = \frac{x}{2\sqrt{\pi}} \int_0^t c_s(\tau) D(\tau) \frac{e^{-V(t-\tau)/\delta - \frac{x^2}{4\Delta I(t, \tau)}}}{\Delta I(t, \tau)^{3/2}} d\tau, \quad (4)$$

where 
$$\Delta I(t, \tau) = \int_{\tau}^t D(s) ds = I(t) - I(\tau),$$

$$I(t) = \int_0^t D(s) ds.$$

In obtaining the solution (4), it has been assumed that the function  $D(t)$  is continuous, positive and bounded for all  $t > 0$ .

It is obvious that if  $D = D_e$  (where  $D_e$  is diffusion coefficient in the case of equilibrium grain boundaries) and  $V = 0$  then it follows of (4) a standard distribution of diffusant from a permanent source on the surface [7].

In setting most of diffusion problems it is considered a source of constant concentration  $c_s = \text{const} > 0$ . Then the expression (4) for diffusant concentration from a constant concentration source is to be determined solely by the form of the diffusion coefficient dependence on time.

In the case of unsteady grain boundaries, the nonequilibrium diffusion coefficient dependence on time takes the form [2]:

$$D(t) = D_e \exp(\Delta E/k_B T), \quad (5)$$

where  $D_e$  diffusion coefficient of equilibrium boundaries per atom,  $T$  annealing temperature,  $k_B$  Boltzmann constant,  $\Delta E$  excess energy of nonequilibrium grain boundaries per atom. To evaluate the relaxation of this energy is used the expression [2]:

$$\Delta E = \Delta E_0 \exp(-t/t_0), \quad (6)$$

where  $\Delta E_0$  is the value of grain boundary excess energy to which relaxation goes, the value of  $t_0$  is a characteristic half-time reduction of the density of grain boundary dislocations introduced (relaxation time). Typical values of the relaxation time can be approximately estimated by the formula [2]:

$$t_0 = \frac{d^3 k_B T}{200 \delta D_e^2 \mu \Omega},$$

where  $d$  the average size of grains,  $D_e^2$  coefficient of grain boundary self-diffusion along equilibrium grain boundaries,  $\Omega$  atomic volume,  $\mu$  shear modulus.

In some cases, integration of (4) can be carried out and in result it can be obtained the explicit expression for the diffusant concentration in diffusing from a source with constant concentration which will be shown below.

#### *Patterns of Diffusion from a Source with Constant Concentration along Nonequilibrium Grain Boundaries Rested on*

If to consider a grain boundary fixed then for diffusion from the constant source when  $c_s = \text{const}$  it is possible to obtain the following expression of (4) at  $V = 0$

$$c(x, t) = c_s \text{erfc}\left(\frac{x}{2\sqrt{I(t)}}\right), \quad (7)$$

taking into account arbitrary kind of dependence of diffusion coefficient on time. Here  $\text{erfc}(z) = 1 - \text{erf}(z)$

where  $\text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-y^2} dy$  the error function. When

$D = D_e = \text{const}$  a standard distribution of concentration follows from (7) for diffusion of a permanent source along equilibrium boundaries [7]:

$$c_s(x, t) = c_s \text{erfc}\left(\frac{x}{2\sqrt{D_e t}}\right). \quad (8)$$

Given (5) and (6) for unsteady grain boundaries we have

$$I(t) = D_e \int_0^{t/t_0} \exp\left(\frac{\Delta E_0}{k_B T} e^{-z}\right) dz. \quad (9)$$

The substitution of this expression into (7) leads to the distribution of diffusant, obtained in [2]. Figure 1 shows typical graphs of the diffusant concentration distribution (7), taking into account the dependence (9). The dimensionless coordinate  $\xi = x/\sqrt{D_e t_0}$  has been introduced to analyze.

It should be noted that the integral (9) can be expressed through the special function  $\text{Ei}(z)$ , called integral exponent:

$$I(t) = D_e \int_0^{t/t_0} \left\{ \text{Ei}\left(\frac{\Delta E_0}{k_B T}\right) - \text{Ei}\left(\frac{\Delta E_0}{k_B T} e^{-t/t_0}\right) \right\}. \quad (10)$$

There is not this presentation in the work [2].

Analysis of the expression (7) using the dependence (10) showed that the distribution of diffusant concentration at a given distance from the sample surface in a fixed time in the presence of excess energy of nonequilibrium grain boundaries will be higher than in the case of equilibrium boundaries. This is due to the dependence (5) of the effective coefficient of grain boundary diffusion for which it grows exponentially with the

increase of excess energy of nonequilibrium boundaries.

When  $k_B T \gg \Delta E_0$  it can be obtained from (7) a simplified expression, fair at sufficiently high temperatures and annealing time significantly exceeding the relaxation time ( $t \gg t_0$ ):

$$c(x, t) = c_s \operatorname{erfc} \left( \frac{x}{2\sqrt{D_e t}} \left( 1 - \frac{t_0 \Delta E_0}{2t k_B T} \right) \right) \approx c_e(x, t) + \frac{x^2}{4\sqrt{\pi D_e t} k_B T} \frac{t_0 \Delta E_0}{k_B T}, \quad (11)$$

where  $c_e(x, t)$  is defined by the expression (8). It follows from (11) that the concentration of diffusant with small nonequilibrium of boundaries increases linearly with the excess energy of nonequilibrium boundaries.

At low temperatures  $k_B T \ll \Delta E_0$  and short-term annealing ( $t \ll t_0$ ) it can be obtained the simplified expression from (7):

$$c(x, t) = c_s \operatorname{erfc} \left( \frac{x}{2\sqrt{D_e t}} \sqrt{\frac{\Delta E_0}{k_B T}} e^{\frac{\Delta E_0}{2k_B T}} \right) \approx c_s \left( 1 - \frac{x}{4\sqrt{\pi D_e t}} \sqrt{\frac{\Delta E_0}{k_B T}} e^{\frac{\Delta E_0}{2k_B T}} \right). \quad (12)$$

It follows from (12) that the concentration of diffusant at strong nonequilibrium boundaries increases with the excess energy of nonequilibrium boundaries.

We define the quantity of penetrating substance for the time  $t$  through a cross-section area of the unit to a depth of  $L$ :

$$Q_L(t) = \int_0^L c(x, t) dx.$$

Substitution of the diffusant distribution (7) leads to the expression:

$$Q_L(t) = c_s \left\{ \frac{2}{\sqrt{\pi}} \left( \sqrt{I(t)} - e^{\frac{L^2}{4I(t)}} \right) + L \operatorname{erfc} \left( \frac{L}{2\sqrt{I(t)}} \right) \right\}. \quad (13)$$

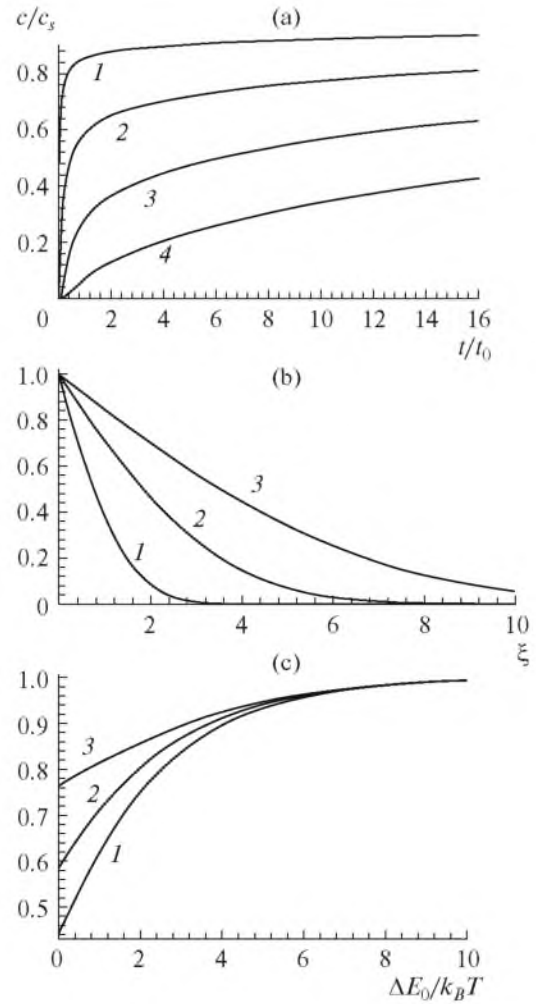
If we consider the bulk sample then it can be considered at a sufficiently large depth  $L \rightarrow \infty$  and

$$Q(t) = \lim_{L \rightarrow \infty} Q_L(t) = \int_0^\infty c(x, t) dx. \quad (14)$$

Such an amount of substance can be calculated by the equivalent formula:

$$Q(t) = - \int_0^t D(\tau) \frac{\partial c(x, \tau)}{\partial x} \Big|_{x=0} d\tau. \quad (15)$$

For bulk samples, calculation by the formulas (14) and (15) coincide in the case of diffusion along unsteady boundaries. From (14), taking into account (7), the simple expression for the diffusant amount



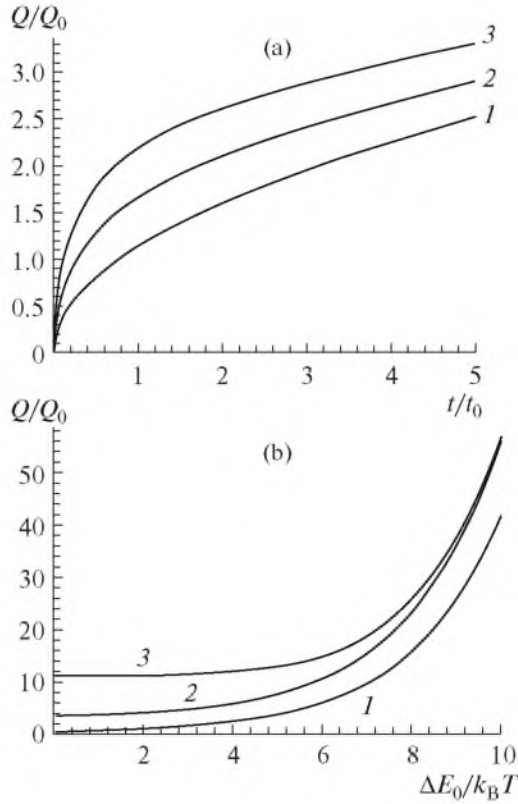
**Fig. 1.** Distribution of the diffusant concentration (7) at fixed temperature and different parameter values: (a)  $\Delta E_0 = 2k_B T$ , curves: 1— $\xi = 0.5$ ; 2— $\xi = 1.5$ ; 3— $\xi = 3$ ; 4— $\xi = 5$ ; (b)  $\Delta E_0 = 2k_B T$ , curves: 1— $t = 0.1t_0$ ; 2— $t = t_0$ ; 3— $t = 10t_0$ ; (c)  $\xi = 0.6$ ; curves: 1— $t = 0.3t_0$ ; 2— $t = 0.6t_0$ ; 3— $t = 2t_0$ .

penetrating for the time  $t$  through a cross-section area of the unit at a great depth is obtained:

$$Q(t) = 2c_s \sqrt{\frac{I(t)}{\pi}} = 2c_s \sqrt{\frac{D_e t_0}{\pi}} \left\{ \operatorname{Ei} \left( \frac{\Delta E_0}{k_B T} \right) - \operatorname{Ei} \left( \frac{\Delta E_0}{k_B T} e^{-t/t_0} \right) \right\}^{1/2}. \quad (16)$$

At sufficiently high temperatures  $k_B T \gg \Delta E_0$  and annealing time significantly exceeding the relaxation time ( $t \gg t_0$ ), it is obtained of (16):

$$Q(t) = 2c_s \sqrt{\frac{D_e t}{\pi}} \left( 1 + \frac{t_0 \Delta E_0}{2t k_B T} \right). \quad (17)$$



**Fig. 2.** Dependences of the diffusant amount (15)  $Q(t)/Q_0$  where  $Q_0 = 2c_s(D_e t_0)^{1/2}$  at fixed temperature and different parameter values: (a) curves: 1— $\Delta E_0 = 0.05k_B T$ ; 2— $\Delta E_0 = 1.2k_B T$ ; 3— $\Delta E_0 = 2k_B T$ ; (b) curves: 1— $t = 0.1t_0$ ; 2— $t = 10t_0$ ; 3— $t = 100t_0$ .

At low temperatures  $k_B T \ll \Delta E_0$  and short-term annealing ( $t \ll t_0$ ), the expression can be obtained from (16):

$$Q(t) = 2c_s \left( \frac{k_B T}{\pi \Delta E_0} D_e t \right)^{1/2} e^{\frac{\Delta E_0}{2k_B T}}. \quad (18)$$

Analysis of expression (16) shows that the diffusant amount penetrating into the sample grows with increasing excess energy of nonequilibrium boundaries. Figure 2 shows the characteristic graphs of the  $Q(t)$  dependence. It is seen that in the case of strong boundary nonequilibrium, i.e. large values of excess energy of nonequilibrium boundaries, as shown in (18), the diffusant amount  $Q(t)$  increases sharply.

#### *Patterns of Diffusion from a Source with Constant Concentration along the Equilibrium Migrating Grain Boundaries*

If we consider now migrating at a constant speed  $V$  boundaries, but not taking into account the dependence of diffusion coefficient on time, it is considered that the diffusion occurs in virtually equilibrium grain

boundaries, then the expression produced in [7] is obtained from (4) with  $D = D_e = \text{const}$ :

$$c(x, t) = \frac{c_s}{2} \left\{ e^{-x\sqrt{V/\delta D_e}} \operatorname{erfc} \left( \frac{x}{2\sqrt{D_e t}} - \sqrt{\frac{Vt}{\delta}} \right) + e^{x\sqrt{V/\delta D_e}} \operatorname{erfc} \left( \frac{x}{2\sqrt{D_e t}} + \sqrt{\frac{Vt}{\delta}} \right) \right\}. \quad (19)$$

From this expression, as noted in [7], it follows that the distribution of diffusant concentration in the grain boundary at a given distance from the sample surface in a fixed time if there is a finite speed of migration of grain boundaries is lower than in the case of resting boundaries. Fig. 3 shows typical graphs of the diffusant concentration distribution (19).

Let us discuss the possible limiting cases clearly reveal the behavior of the dependence (19). At large distances from the surface of the sample with  $x \gg (D_e t)^{1/2}$  it follows from (19) that the concentration of diffusant concentration quickly decreases under the law:

$$c(x, t) = 2c_s \sqrt{\frac{D_e t}{\pi}} \frac{e^{-\frac{x^2}{4D_e t} - \frac{Vt}{\delta}}}{x}. \quad (20)$$

Close to the surface when  $x \ll (D_e t)^{1/2}$  (19) shows that the diffusant concentration decreases in a linear on  $x$  law:

$$c(x, t) = c_s \left\{ 1 - \frac{x}{\sqrt{\pi D_e t}} \left[ e^{-\frac{Vt}{\delta}} + \sqrt{\frac{\pi V t}{\delta}} \operatorname{erfc} \left( \sqrt{\frac{Vt}{\delta}} \right) \right] \right\}. \quad (21)$$

At large annealing time, saturation of the sample by diffusant takes place, and its concentration reaches a value

$$c_\infty(x) = c_s e^{-x\sqrt{V/\delta D_e}}. \quad (22)$$

At low migration speeds of grain boundaries ( $V \ll \delta/t$ ), (19) shows that the diffusant concentration linearly depends on the speed of migration:

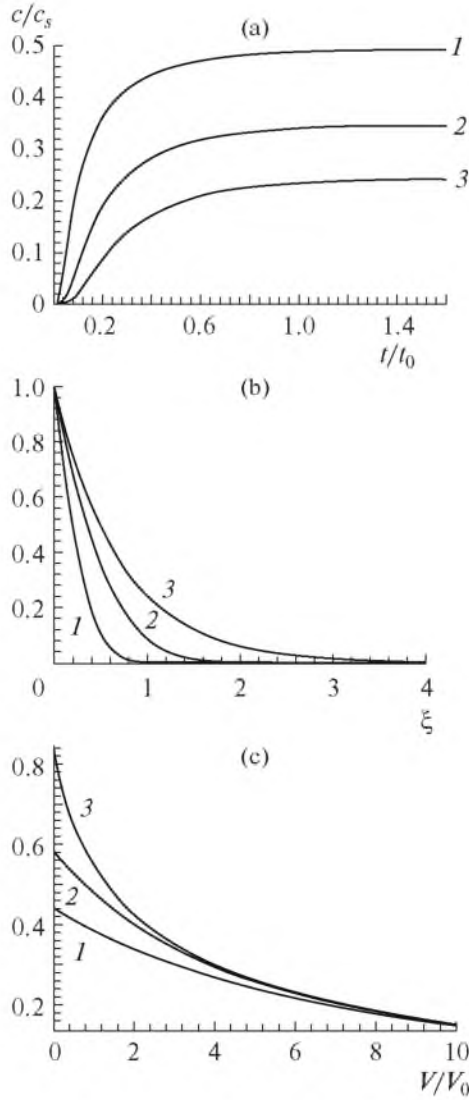
$$c(x, t) = c_s(x, t) - c_s \frac{xV}{\delta D_e} \left\{ 2\sqrt{\frac{D_e t}{\pi}} e^{-\frac{x^2}{4D_e t}} - \frac{x}{2} \operatorname{erfc} \left( \frac{x}{2\sqrt{D_e t}} \right) \right\}. \quad (23)$$

At high migration speeds of grain boundaries ( $V \gg \delta/t$ ), (19) implies that the diffusant concentration decreases with increasing speed of migration by law:

$$c(x, t) = c_\infty(x) - \frac{c_s x}{\sqrt{\pi D_e t}} e^{-\frac{x^2}{4D_e t} - \frac{Vt}{\delta}}. \quad (24)$$

The profiles of the diffusant average concentration and the amount of substance penetrating for the time  $t$  through a cross-section area of the unit have been calculated in [7] on the base (19). Calculations of  $Q(t)$  can be made by the formula (13) with  $D = D_e = \text{const}$ . As a result we have the expression that differs from one set in [7]:

$$Q(t) = c_s \sqrt{\frac{\delta D_e}{V}} \left\{ \sqrt{\frac{Vt}{\pi \delta}} e^{-\frac{Vt}{\delta}} + \left( \frac{1}{2} + \frac{Vt}{\delta} \right) \operatorname{erf} \left( \sqrt{\frac{Vt}{\delta}} \right) \right\}. \quad (25)$$



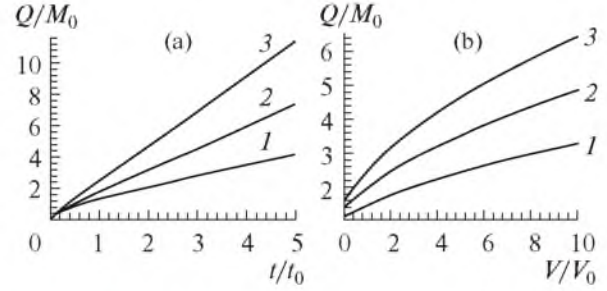
**Fig. 3.** Distribution of the diffusant concentration (22) at fixed temperature and different parameter values: (a)  $V = 2V_0$ , curves: 1— $\xi = 0.5$ ; 2— $\xi = 0.75$ ; 3— $\xi = 1$ ; (b)  $V = 2V_0$ , curves: 1— $t = 0.05t_0$ ; 2— $t = 0.2t_0$ ; 3— $t = 20t_0$ ; (c)  $\xi = 0.6$ ; curves: 1— $t = 0.3t_0$ ; 2— $t = 0.6t_0$ ; 3— $t = 4t_0$ .

Figure 4 shows typical graphs of the dependence of substance amount (25). In [7] it has been noted that the total amount of penetration into the sample material is increased by diffusion along migrating boundaries. This conclusion follows from the above correct expression (25) for the amount of substance.

At large annealing time (25) implies that the substance amount penetrating in a sample grows to a linear law over time:

$$Q(t) = \frac{c_s}{2} \sqrt{\frac{\delta}{VD_e}} \left( 1 + \frac{2Vt}{\delta} \right). \quad (26)$$

Such a behavior at large times of annealing is marked in [7] and it can be seen in Fig. 4a.



**Fig. 4.** Dependences of the diffusant amount (24)  $Q(t)/M_0$  where  $M_0 = c_s(\delta D_e)^{1/2}$  at fixed temperature and different parameter values: (a) curves: 1— $V = 0.5V_0$ ; 2— $V = 2V_0$ ; 3— $V = 5V_0$ ; (b) curves: 1— $t = t_0$ ; 2— $t = 1.5t_0$ ; 3— $t = 2t_0$ .

From (25) with small grain boundary migration velocities ( $V \ll \delta/t$ ), it follows that the substance amount penetrating in a sample grows to a linear law over time too:

$$Q(t) = 2c_s \sqrt{\frac{D_e t}{\pi}} \left( 1 + \frac{Vt}{3\delta} \right). \quad (27)$$

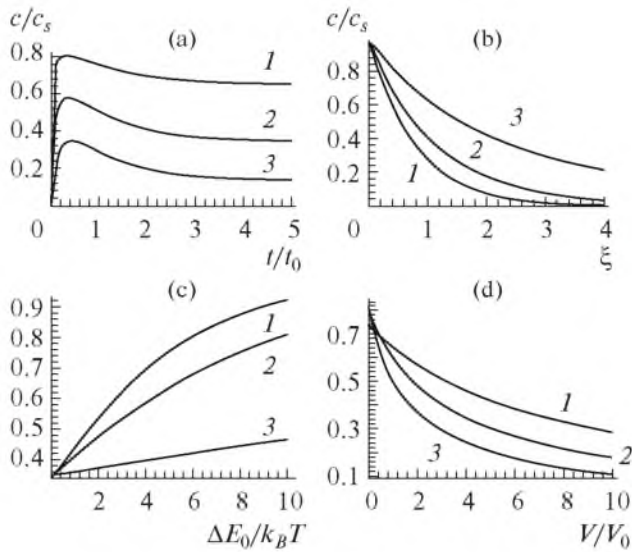
This pattern can be seen in Fig. 4b.

#### *Patterns of Diffusion from a Source with Constant Concentration along Nonequilibrium Migrating Grain Boundaries*

Let us discuss now features of diffusion from a constant source provided that the grain boundaries are both migratory and nonequilibrium. In this case, you should use the expression (4)  $c_s = \text{const}$ . Typical distribution graphs of diffusant concentration from numerical integration (4) are shown in Fig. 5.

Numerical analysis showed that for diffusion along nonequilibrium and migratory boundaries the diffusant concentration dependence on annealing time changes qualitatively: it ceases to be monotonous (Fig. 5a). In some, relatively small, annealing time, a maximum of concentration is observed. With increasing annealing time, the concentration of diffusant slightly decreases and then remains constant reaching a saturation value.

Distribution of the diffusant concentration over the depth of penetration into the sample by diffusion along nonequilibrium and migratory boundaries (Fig. 5b) qualitatively does not differ from similar dependences by the diffusion along both equilibrium migrating boundaries (Fig. 1b) and nonequilibrium resting boundaries (Fig. 3b). It should be noted that nonequilibrium of boundaries facilitates deeper penetration of diffusant in the sample than the migration of boundaries. From comparison Fig. 1b and Fig. 3b one can see that at the same annealing time, the concentration of diffusant by diffusion along migrating boundaries decreases much faster than by diffusion along nonequilibrium boundaries. This means that the



**Fig. 5.** Distribution of the concentration (4) by diffusion from a permanent source at fixed temperature and different parameter values: (a)  $V = 2V_0$ ,  $\Delta E_0 = 2k_B T$ , curves: 1— $\xi = 0.3$ ; 2— $\xi = 0.75$ ; 3— $\xi = 1.4$ ; (b)  $V = 2V_0$ ,  $t = t_0$ , curves: 1— $\Delta E_0 = 0.5k_B T$ ; 2— $\Delta E_0 = k_B T$ ; 3— $\Delta E_0 = 5k_B T$ ; (c)  $V = 2V_0$ ,  $\xi = 0.75$ , curves: 1— $t = 0.8t_0$ ; 2— $t = 1.3t_0$ ; 3— $t = 3t_0$ ; (d)  $\Delta E_0 = 2k_B T$ ,  $\xi = 0.75$ , curves: 1— $t = 0.5t_0$ ; 2— $t = 1.2t_0$ ; 3— $t = 3t_0$ .

depth of diffusant penetration in the sample is determined to a greater degree of nonequilibrium of grain boundaries than their migration. In other words, the main mechanism of grain boundary diffusion, contributing to deeper diffusant penetration, is the diffusion along nonequilibrium boundaries.

On the basis of numerical analysis (4), it is found that at a given depth and a fixed speed of migration the diffusant concentration monotonically increases with increasing the excess energy of nonequilibrium boundaries (Fig. 5c). The monotonically increasing diffusant concentration is observed in the case of diffusion along nonequilibrium resting boundaries (Fig. 1c). However, the finite speed of boundary migration yields that at large values of excess energy of nonequilibrium boundaries the concentrations of diffusant have different values in fixed annealing times but does not converge to one line as for resting boundaries.

Increasing the migration speed of boundaries leads to lower the diffusant concentration. The diffusant concentration dependence on the migration speed of boundaries has a monotonic character (Fig. 5d). However, by the diffusion along nonequilibrium and migratory boundary the concentration values at a fixed depth with relatively high migration speeds do not converge at different times of annealing in one line, as in the case of diffusion along the equilibrium migratory boundaries (Fig. 3c). This difference of concentration profiles can be used to determine the type of

diffusion, i.e. to show that the diffusion goes along nonequilibrium migrating boundaries.

## CONCLUSIONS

In this paper, the model of grain boundary diffusion of a permanent source along migratory nonequilibrium grain boundaries is proposed. Nonequilibrium of grain boundaries causes the dependence of the grain boundary diffusion coefficient on time. Nonequilibrium of grain boundaries of the model is characterized by their excess energy which they relax to. The migration of grain boundaries going at a constant speed results in decreasing rate of change of the diffusant concentration. Accounting migration of grain boundaries leads to modification of the diffusion equation.

Resulting in the proposed model the expression (4) can describe the distribution of the diffusant concentration both in the model applicable for fixed nonequilibrium grain boundaries [2] and in the model applicable for migrating grain boundaries, with constant diffusion coefficient [7]. It is shown on basis of both the analytical expressions and the numerical analysis that increasing excess energy of nonequilibrium boundaries, as well as their speed of migration, leads to increasing the diffusant amount penetrating into the sample during annealing. The concentration profiles calculated in the work can be used to determine the nature of diffusion observed in the diffusion experiments with nanoscale structure materials: whether grain boundaries are nonequilibrium or migratory or they have these two properties at the same time.

It should be noted that the use of an arbitrary dependence of diffusion coefficient on time (anything other than (5)) is necessary in connection with the development of techniques of diffusion-controlled processes in the various technologies to create new nanostructured materials. In particular, the account of the diffusion coefficient dependence on time can be used to control the process of establishing the stationary distribution of impurities in the crystal [8].

Continuous change of the diffusion coefficient in time can be obtained by continuously changing the temperature of the crystal since the diffusion coefficient depends on temperature according to the exponential law  $D(t) = D_0 \exp(-E_d/k_B T(t))$  where  $T(t)$  test temperature changing over time,  $E_d$  activation energy of diffusion and migration,  $D_0 = a^2 v$ ,  $a$  and  $v$  are length and frequency of jumpings, respectively. Thus, controlling the temperature dependence on time  $T(t)$ , one can analyze the diffusion-controlled processes that are important to the technology of nanostructured heat-proof alloys [6].

## ACKNOWLEDGMENTS

This work was supported by the grants of Belgorod State University and the RFBR grant 09-01-00086.

## REFERENCES

1. Grabovetskaya, G.P., Mishin, I.P., Ratochka, I.V., et al., *Pis'ma Zh. Tekh. Fiz.*, 2008, vol. 34, no. 4, p. 1.
2. Nazarov, A.A., *Fiz. Tverd. Tela*, 2003, vol. 45, no. 6, p. 1112 [*Phys. Solid State* (Engl. Transl.), vol. 45, no. 6, p. 1166].
3. Perevezentsev, V.N., Pupynin, A.S., and Svirina, Yu.V., *Fiz. Met. Metalloved.*, 2002, vol. 94, no. 2, p. 28.
4. Perevezentsev, V.N., Pupynin, A.S., and Svirina, Yu.V., *Fiz. Met. Metalloved.*, 2005, vol. 100, no. 1, p. 17.
5. Perevezentsev, V.N. and Pupynin, A.S., *Fiz. Met. Metalloved.*, 2008, vol. 105, no. 4, p. 350.
6. Kolobov, Yu.R., *Diffuzionno-kontroliruemye protsessy na granitsakh zeren i plastichnost' metallicheskih polikristallov* (Diffusion-Controlled Processes at Grain Boundaries and Plasticity of Metal Polycrystals), Novosibirsk: Nauka, 1998.
7. Kaur, I., Mishin, Y., and Gust, W., *Fundamentals of Grain and Interphase Boundary Diffusion*, Chichester: Wiley, 1995.
8. Pankratov, E.L., *Zh. Tekh. Fiz.*, 2004, vol. 74, no. 1, p. 115.