

FORMATION OF STEP DENSITY SHOCK WAVES ON VICINAL NaCl(100) GROWTH SURFACES

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The morphology of the growth surface near NaCl(100), formed during the pore motion in a crystal due to the temperature gradient, has been studied by the electron microscopic method of vacuum decoration. It is shown that at $T = 950$ K and $\Delta\mu/kT = 4 \cdot 10^{-3}$, the profile of the vicinal surface in the $\langle 11 \rangle$ direction is represented by monoatomic steps, while in the $\langle 10 \rangle$ direction, as the surface curvature increases, there is a grouping of steps with the formation of macrosteps – bunches of elementary steps separated by areas of atomically smooth terraces. The sawtooth dependence of the step density on the longitudinal coordinate is described by a particular solution of the Burgers equation for a shock wave. Data on the parameters of three shock waves and the time of their formation are obtained.

INTRODUCTION

It is known that vicinal surfaces during the growth of crystals from the vapor phase or solutions are subject to a certain type of morphological instability – bunching of steps [1–4]. The formation of step bunching is a very serious problem when growing perfect crystals and obtaining surfaces that are atomically smooth on a macroscale [5–7]. On the other hand, such instabilities lead to the formation of large-scale nanostructured surfaces, which can be used to obtain low-dimensional structures actual for various technological applications [8–14]. A theoretical description of the nonlinear processes that result in the development of such kind of instabilities is very complicated due to a variety of causes leading to the step bunching in real experimental conditions (presence of impurities, surface electromigration effect, Ehrlich-Schwöbel effect, elastic stress fields, variable macroscopic fields, non-quasi-static effects, etc.) [15–20]. The current state of research of step bunching, in particular, induced by electric currents, is presented in the references given in [21], where it is shown how the general picture of the process of bunching depends on the short-range repulsive force between the steps. It is customary to distinguish between the step bunching as a result of morphological instability and as a shock in a kinematic wave, when the flux of steps is determined only by their local density [3].

The reference equation describing nonlinear waves in a dissipative nondispersive medium is the Burgers equation (BE) [22]. Since dissipation is high-frequency, its effect is strongest where the wave profile changes most rapidly, i.e. near its front. For this reason, in wave theory, a steep and thin wave front at the moment when the steepening process stops is usually called a shock wave [3]. It is generally accepted that because the shock

corresponds to the location of an abrupt change in density, let us say a transition from high to low density at a very short length, shock waves are not actual bunches, but rather their edges. However, if we talk about stationary shock waves of the BE, it is worth to introduce the concept of shock wave amplitude as the difference between the maximum and minimum values of the wave profile, as well as the characteristic width of the front – the longitudinal distance at which the difference in these values occurs. The coefficient μ at the second derivative in the BE is an analogue of viscosity.

The study of kinematic (“shock”) waves of steps on crystal surfaces was first carried out by Frank [23], and by Cabrera and Vermilyea [24], who used the results of the general analysis of kinematic waves done by Lighthill and Whitham [25]. Later, it was shown in [26] that during crystal growth from the vapor phase, the shock wave is the main result of diffusion interaction of moving steps and exhibits itself as an edge at which the slope of the vicinal surface changes sharply. A characteristic feature of shock waves is the presence of discontinuities in the step density. The density discontinuity can arise under a wide variety of perturbations, if only these perturbations result in areas on the surface where the density of steps has increased in absolute value.

It is known that not only dissipation, but also dispersion are among the factors that can stop the steepening of a wave and prevent it from overturning. In the general case, the dynamics of the profile of a macroscopic curved vicinal surface of a crystal growing from the vapor phase was studied in [27]. In this work, expressions for the average values of adatom concentration and the velocity of elementary steps were obtained by averaging over large spatial intervals. The nonlinear Korteweg de Vries-Burgers (KVB) equation

was obtained from the continuity equation for average values of the adatom concentration and velocity of the elementary steps, on the condition that the surface curvature is phenomenologically considered [3, 28]. This equation describes the nonlinear dynamics of motion of a train of parallel elementary steps on a macroscopically curved vicinal crystal surface. In a particular case, the KVB equation transforms into the BE, which describes the formation and dynamics of shock waves.

In [29], particular solutions of the BE with zero boundary conditions were obtained in an analytical form. It is shown, in particular, that for a shape parameter of the initial perturbation greater than one, its amplitude nonmonotonically depends on the spatial coordinate. Over time, the shock wave does not form, and the perturbation amplitude decreases exponentially and tends to zero. A particular solution for the first mode was used to describe the configuration of elementary steps with an orientation near $\langle 100 \rangle$, formed at the base of the cleavage macrostep during the growth of a NaCl crystal from the vapor phase. It was shown that the one-dimensional distribution of the step concentration adequately reflects the shock wave profile at the decay stage. At small values of the shape parameter, particular solutions describe the shock wave formation from initial periodic perturbations.

In this work, the obtained solutions are used to describe some experimental results associated with the formation of shock waves of the elementary step density during the growth of NaCl single crystals from the vapor phase.

EXPERIMENTAL PROCEDURE

Reasons for the choice of alkali halide crystals, in particular NaCl, as objects for the study of kinematic density waves of elementary steps are described in detail in [27, 29]. The main argument is the possibility to exclude practically the causes listed in the introduction that lead to the bunching of steps as a result of the “morphological instability” of the vicinal surface. By studying in these crystals the processes of motion and transformation of the shape of pores and inclusions of saturated solution, one can obtain important features of layer-by-layer mass transfer [30–33]. Varying as the only external parameter, the temperature between opposite crystal faces, one can create unique conditions for crystallization (decrystallization) at low supersaturation, which are very difficult to realize in traditional growth experiments.

The morphology of the growth (evaporation) surfaces of NaCl single crystals is well studied. Data on kinetic and thermodynamic characteristics of layer-by-layer mass transfer on the vicinal surfaces of these crystals were obtained in a wide temperature range (see references in [27]). It was shown that the doubled value of the linear tension of monatomic height steps is less than the linear tension of double-height steps, which indicates the thermodynamic stability of the studied NaCl(100) vicinal surfaces.

Samples with pores were prepared using the known technique – healing unfinished crack, which consists of the following. Rectangular $10 \times 10 \times 3$ mm plates were

cut from the single crystals, and then they were partially split parallel to the large faces. After that, the crystal with an unfinished crack was compressed and annealed under isothermal conditions at the pre-melting temperature. While annealing the crack was healing and closed pores of $1 \dots 100 \mu\text{m}$ in size, faceted by planes $\{100\}$ and with rounded vertices, were forming in its mouth. All pores were in the same plane, and this allowed one to follow not only individual pores, but also entire ensembles using transmission optical microscopy.

The pore motion was in the direction of the temperature gradient ∇T coinciding with the crystal axis $\langle 001 \rangle$ [27]. During the motion, the shape of most pores became more faceted and took the form of parallelepipeds elongated in the direction perpendicular to the temperature gradient. This indicated that evaporation processes, in addition to the front surface, occurred on the four lateral pore surfaces, and growth processes occurred on one, i.e. just the back surface. The samples with pores were split in a vacuum setup and the opened pore surfaces were examined using the electron microscopic technique of vacuum decoration.

The pore motion under the temperature gradient ∇T in the crystal is caused by the difference in the chemical potentials $\Delta\mu$ of molecules on the front and back surfaces, which is expressed by the ratio $\Delta\mu = \Delta H \nabla T Z / T$, where ΔH is the evaporation heat; Z is the pore linear size in the direction of the gradient. Varying the value of the temperature gradient, it was possible to study the processes of evaporation-growth in a wide range of under- and supersaturation ($\Delta\mu/kT$).

Since the growth-evaporation (dissolution) processes occur in layers in alkali-halide crystals, it is obvious that layer sources are necessary for the motion of pores (inclusions of a saturated solution). Such sources for growth are edges of pores (inclusions). As for evaporation (dissolution), at low undersaturation, the only possible layer sources may be the steps formed in the places where screw dislocations come to the surface [30–32].

Faceted shapes of pores (liquid inclusions) and an increase in the degree of shape nonisometry in the perpendicular direction mean that the limiting process during the pore (inclusion) motion is the evaporation (dissolution) of the matrix substance, rather than its transfer through the pore (inclusion) volume. In the case of saturated solution inclusions, their unchanged shape during the motion induced by driving forces of different nature (inhomogeneous density distribution of dislocations or radiation defects, see [32, 33] and references therein) indicates the limiting role of the diffusion process of the matrix substance through the inclusion volume. In this case, the difference in the molecules' chemical potential between the front and back surfaces will be mostly not near the front surface, but along the entire inclusion length in the direction of the driving force.

It is clear that the energy, required to embed molecules into edges on growing surfaces, is much less than the energy required to form a critical nucleus on a screw dislocation. This explains the significant difference in the morphology of the evaporation and

growth surfaces within the pores [27, 31]. While the evaporation surfaces are practically smooth on an atomic scale, the growth ones can be represented by trains of steps whose length is comparable to the pore size. That makes them a unique object for studying the kinematic waves of elementary step density on vicinal surfaces of the investigated crystals. Since the recrystallization of the matrix material occurs inside the pore, the effect of impurities on the kinetics of elementary step motion, which takes place in traditional growth experiments at low supersaturations, is practically excluded.

EXPERIMENTAL RESULTS

Fig. 1 shows an area of the pore growth surface formed at low supersaturation. Taking $Z = 13 \mu\text{m}$, $\Delta H = 3.9 \cdot 10^{-19} \text{ J}$ [34] at $\nabla T = 1 \cdot 10^{-4} \text{ K/m}$ and $T = 950 \text{ K}$, we have $\Delta\mu/kT = 4 \cdot 10^{-3}$. The motion of the train of steps with an orientation near $\langle 10 \rangle$ selected for analysis occurs from the pore edge (outside Fig. 1, above the area in it) in the $\langle 0\bar{1} \rangle$ direction. The tangential motion of steps results in the overgrowth of concentric layers and provides the normal displacement of the surface.

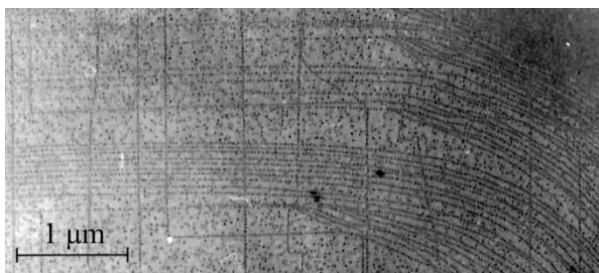


Fig. 1. TEM image of the growth surface near NaCl(100), formed during the pore motion under the temperature gradient (linear steps appeared at the splitting of the crystal in vacuum)

An important feature of the morphology of the investigated surface is the difference in its profile for the $\langle 10 \rangle$ and $\langle 11 \rangle$ directions. In the $\langle 11 \rangle$ direction, the vicinal surface profile is represented by monoatomic steps, at least up to those surface curvature values at which the decoration technique still allows to resolve individual steps. The fact that the steps are monoatomic can be concluded from the intersections of the step trains by slip bands [35], which appear when the crystal is split in vacuum and the pore surfaces are opened. Whereas in the $\langle 10 \rangle$ direction, as the curvature of the surface increases, the formation of macrosteps is observed. In this case, by “macrosteps” we mean bunches of elementary steps, rather than “true steps” [26], whose thermodynamic stability is determined by the anisotropy of the surface energy. It was shown earlier that vicinal surfaces near NaCl(100) are thermodynamically stable, i.e. the integration of monoatomic steps into higher ones is thermodynamically unfavorable. There are no effects that can lead to the formation of thermodynamically stable macrosteps on these surfaces (see [2] and references therein). Therefore, we use the term “macrostep” to name a bunch of elementary steps, which is a

part of a kinematic wave or a shock wave of step density [3, 26].

Analysis of the surface morphology in Fig. 1 shows that such macrosteps are difficult to distinguish from elementary steps in the decoration patterns. They are represented by similar chains of decorating gold particles, the sizes of which vary from 40 to 100 Å. The height a of a monoatomic step is 2.81 Å and the number of elementary steps included in the observed macrosteps does not exceed one or two dozen. The number of elementary steps forming a particular macrostep with the $\langle 10 \rangle$ direction can be estimated by the number of elementary steps branching off from it. To reduce the error in determining the macrostep heights, the selected area of the pore surface was digitized in the $\langle 01 \rangle$ and $\langle 11 \rangle$ directions. Comparison of the obtained data allowed a sufficiently reliable reconstruction of the surface profile in the $\langle 01 \rangle$ direction (within 75 elementary steps from the central concentric layer).

The fact that the monoatomic steps do not integrate to form a “true” macrostep but form a bunch of steps is also confirmed by direct observations of the disintegration of steps formed on screw dislocations with a Burgers vector $2a$ into two monoatomic ones at small super-/undersaturation ($\leq 10^{-2}$) [36], i.e. at conditions when kinetic factors are not so significant. Therefore, when digitizing the trains of steps in Fig. 2, the bunch width was determined with an error of the order of the size of decorating particles. And when determining the step density in the bunch, we took into account the width of the adjacent terrace on the side of the nearest distinguishable step.

A characteristic feature of shock waves described by the BE particular solutions [29] is a sawtooth profile of the wave surface. As applied to kinematic density waves of elementary steps on thermodynamically stable vicinal surfaces, this means the presence of discontinuities in step density, accompanied by the formation of relatively wide atomic-smooth terraces, as well as the redistribution of elementary steps with the formation of bunches – macrosteps. Three bunches of steps in Fig. 1, formed in the immediate vicinity of the pore edge, satisfy this description.

The dependence of the step concentration (dimensionless density) averaged over several adjacent terraces on the longitudinal coordinate in units λ_s (see Fig. 2) was plotted using the step distribution in bunches, taking into account the width of adjacent terraces, obtained due to digitization.

DESCRIPTION OF THE EXPERIMENTAL RESULTS OF NaCl CRYSTAL GROWTH FROM THE VAPOR PHASE BY THE BE PARTICULAR SOLUTION

In [29], a particular BE solution with zero boundary conditions was used for the first time to carry out a quantitative analysis of the decay of shock waves. In this work, a particular BE solution with zero boundary conditions was used to describe the decay of the profile of a one-dimensional echelon of elementary steps with an orientation near $\langle 100 \rangle$, which was formed during the growth of a NaCl single crystal from the vapor phase at

the base of a macroscopic cleavage step. It is shown that the distribution of the step concentration with distance from the initial position of the macrostep adequately reflects the shock wave profile at the decay stage. The dimensionless parameters of the shock wave are determined, and on their basis the estimates of the characteristic time of its decay are made.

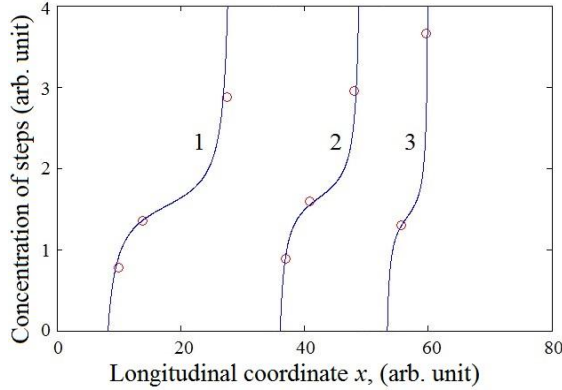


Fig. 2. The structure of the shock waves shown in Fig. 1: symbols are the experimental values of the average concentration of steps in the wave (the wave propagation direction is inverted relative to the step motion direction); solid lines are the calculation results based on the particular solution (7) at $n=1$

To describe the inverse process of shock wave formation, it is necessary to change the formulation of the problem in terms of reformatting the boundary conditions. Since crystal growth occurs from the vapor phase, a source of adatoms is required. Based on this, we formulate the problem of crystal growth, using BE to describe this process.

Let us find the bounded BE solutions $|u(x,t)| < \infty$ on the interval $0 \leq x \leq L$ in the time interval $0 \leq t < t_0 < \infty$:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = \mu \frac{\partial^2 u}{\partial x^2} \quad (1)$$

with boundary conditions:

$$u(0,t) = 0, \quad u(L,t) = A \cdot (t_0 - t \cdot f(t))^{-1}, \quad (2)$$

where t, x are the dimensionless time and coordinate, respectively; $\mu > 0$ is the dimensionless coefficient of kinematic viscosity of the medium; $A > 0, t_0$ are constants, $B_{\min} \leq f(t) \leq B_{\max}$ is a positive definite function bounded on both sides. The values of constants B_{\min}, B_{\max} will be defined below.

The boundary condition at $x = L$ modelically describes the source of adatoms that come to the growing crystal surface from the vapor phase. The boundedness of the solution $|u(x,t)| < \infty$ is provided by the condition $|A/(t_0 - B_{\max}t)| < D$ that is feasible for $t_0 > B_{\max}t$ at a finite value of D .

The Cole-Hopf transformation (CH) $u(x,t) = -2\mu \frac{1}{v(x,t)} \frac{\partial v(x,t)}{\partial x}$ converts the nonlinear equation (1) into a linear heat equation for the function $v(x,t)$:

$$\frac{\partial v(x,t)}{\partial t} = \mu \frac{\partial^2 v(x,t)}{\partial x^2}. \quad (3)$$

The CH transformation imposes a condition on the function $v(x,t)$: $v(x,t) \neq 0$.

As a result of the CH transformation, the boundary conditions (2) for equation (3) take the form:

$$\frac{\partial v(0,t)}{\partial x} = 0, \quad \frac{\partial v(L,t)}{\partial x} = C \exp\left(-\frac{A \cdot L}{2\mu(t_0 - t \cdot f(t))}\right), \quad (4)$$

where C is the constant of integration.

Equation (3) has an infinite number of particular solutions that satisfy the boundary condition (4) for $x = 0$ [29]:

$$v_n(x,t) = \cos(\lambda_n x) \exp(-\mu \lambda_n^2 t), \quad (5)$$

where $\lambda_n = n\pi/L, n = 1, 2, 3, \dots$

Particular solutions (5) are determined up to a positive constant a_n and a function $\varphi_n(x,t) = \pm b_n(t + x^2/2\mu)$, where b_n is a positive constant.

Therefore, new functions of the form:

$$w_n(x,t) = \cos(\lambda_n x) \exp(-\mu \lambda_n^2 t) + a_n \pm b_n \left(t + \frac{x^2}{2\mu}\right) \quad (6)$$

are also particular solutions of equation (3). It is easy to verify that solutions (6) satisfy boundary conditions (4).

As a result of the CH transformation we obtain the particular solutions of the BE:

$$u_n(x,t) = \frac{2\mu \lambda_n \sin(\lambda_n x) \exp(-\mu \lambda_n^2 t) \mp 2b_n x}{\cos(\lambda_n x) \exp(-\mu \lambda_n^2 t) + a_n \pm b_n \left(t + \frac{x^2}{2\mu}\right)}, \quad (7)$$

where $b_n > \mu \lambda_n^2, a_n > b_n L^2 / 2\mu + 1$.

Expression (7) describes an infinite number of BE particular solutions for different values of the constants.

Let us consider solutions (7) with the lower sign of the last term of the numerator and denominator. In this case, there are solutions describing the steepening of the shock wave profile. Consider such solutions for the mode $n = 1$ and values of constants: $A = 2b_1 L, t_0 = a_1 - b_1 L^2 / 2\mu - 1 > 0$. The function $f(t)$ in (2) must be specified in the form of

$$f(t) = b_1 - \frac{1 - \exp(-\mu \lambda_1^2 t)}{t}, \quad \text{when the condition}$$

$b_1 > \max(\mu \lambda_1^2, 1)$ is met. The inequality $b_1 > 1$ follows from the condition that the denominator $u(L,t)$ in (2) tends to zero as $t \rightarrow t_0$. For the function $f(t)$ we have the limits of its change: $B_{\min} = b_1 - \mu \lambda_1^2$ and

$$B_{\max} = b_1 - \frac{1 - \exp(-\mu \lambda_1^2 t_0)}{t_0} < b_1.$$

The condition $b_1 > \max(\mu \lambda_1^2, 1)$ is fulfilled if we put, for example, $b_1 = 1 + \mu \lambda_1^2 (1 - e^{-\mu \lambda_1^2 t_0})$, as $b_1 > 1$ at $\mu \lambda_1^2 \ll 1$, and $b_1 > \mu \lambda_1^2$ at $\mu \lambda_1^2 > 1$. Based on this assumption, let us determine the characteristic time of shock wave formation.

The characteristic time of shock wave formation is estimated from the value of the time when the denominator (7) tends to zero, but the amplitude of the disturbance is limited by the condition of the BE applicability. The denominator feature arises for $x = L$ and characteristic "explosion" time may be determined from the equation:

$$\xi = -\ln\left(1 - (1 - \exp(-\zeta))\zeta^{-1}\right), \quad (8)$$

where $\xi = \mu\lambda_1^2$, $\zeta = \mu\lambda_1^2 t_0$.

It is easy to see that equation (8) has a simple solution: $\mu\lambda_1^2 = 1$, $t_0 = 1$. At critical points from (8) we have: at $\zeta \rightarrow 0$ the value ξ tends to infinity $\xi \rightarrow \infty$; at $\zeta \rightarrow \infty$ the value ξ tends to zero $\xi \rightarrow 0$.

From (8) we can determine the characteristic "explosion" time via the parameter ζ :

$$t_0 = -\zeta \left[\ln\left(1 - (1 - \exp(-\zeta))\zeta^{-1}\right) \right]^{-1}. \quad (9)$$

Using (9), it is possible to determine graphically the dependence of the "explosion" time on the parameter $\mu\lambda_1^2$ (Fig. 3).

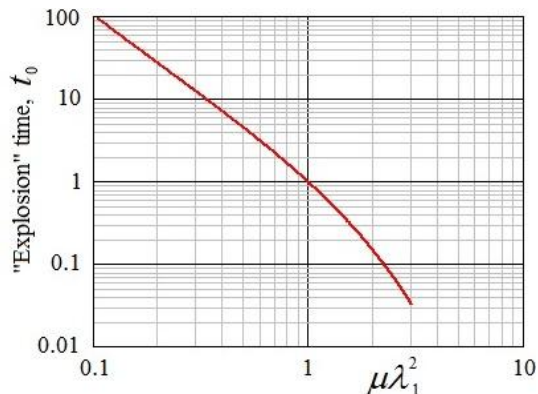


Fig. 3. The dependence of the "explosion" time on the parameter $\mu\lambda_1^2$

From Fig. 3 it follows that with an increase of wave period, the "explosion" time increases. The "explosion" time also increases with decrease in the coefficient of kinematic viscosity of the medium at a constant wave period.

The characteristic "explosion" time of shock wave will be determined on the basis of the experimental data presented below.

The obtained experimental data were processed according to the method previously used to describe the shock wave decay during the growth of a NaCl single crystal from the vapor phase [29]. Estimates of the coefficient μ [27] taking into account the equilibrium concentration of admolecules on atomic-smooth areas of the surface $\xi_{a0} \sim 10^{-6}$ (according to the data in [34]) with a known value of $\lambda_s = 3.37 \cdot 10^{-8}$ m [27] and the average value $\rho_0\lambda_s \approx 0.8$, obtained by digitization, showed that $\mu \sim 1$ at $q \sim 0.1$ ($\rho_0\lambda_s$). Exactly of such order is the value of the parameter $v \sim q / (\rho_0\lambda_s)$ [29], if we take $q \sim 1/2 \bar{L}$, where \bar{L} is the average value of the half-width of the wave front in Fig. 2.

Using the software products Wolfram Mathematica and Mathcad, the experimental dependences of the steps

concentration of shock waves on their coordinates were approximated by theoretical dependences at $\mu = 1.19$. Parameters of three shock waves (Table) were obtained as a result of processing the experimental data of Fig. 2 on the basis of expression (7) at $n = 1$.

The following features of the shock waves under study are noteworthy. First, their formation occurs for the <10> directions and is not observed in the <11> directions, which allows us to determine the number of elementary steps included in each wave: 18, 14, and 10, respectively. This distinction of the surface profiles can be due to both the difference in the nature of the thermodynamic interaction between the steps in the indicated directions [36], and the difference in the diffusion-kinetic interaction. Indeed, as the step orientation deviates from the direction of close packing, the concentration of kinks on the step increases significantly, reaching a maximum for the orientations <11>. Consequently, the kinetic coefficients, characterizing the rate of admolecule incorporation into the <11> steps, are much greater than the kinetic coefficients of the <10> steps.

Parameters of the shock waves in Fig. 2

No.	$\rho_0\lambda_s$	L	a_1	b_1	t
1	0.669	9.90	63	1.12	4.0
2	0.750	6.58	80	1.27	2.0
3	1.111	2.78	130	2.53	0.3

Second, macrosteps, i.e. bunches of elementary steps, are formed under the condition that the average (initial) width of the terraces does not exceeds $2\lambda_s$, i.e. diffusion fields on the terraces of adjacent steps overlap. As the degree of overlap increases, the width of the wave front and the time of its formation decrease. Meanwhile, since the number of steps involved in the wave formation decreases, the wave amplitudes differ slightly.

The faster formation of waves as they approach the pore edge and the steepening of their profile are caused by an increase in the average local curvature of the macroscopic surface as it approaches the edge of the pore. At that, both the intensity of diffusion interaction of the steps and the intensity of their thermodynamic interaction increase [36].

The obtained value of the coefficient μ , as well as the parameters a_1, b_1 and the front half-width L , allow us to estimate the characteristic "explosion" time t_0 on the basis of relation (8), (9). The experimental values of "explosion" time for shock waves 1, 2, 3 t_{exp} are shown in Table and less than t_0 .

CONCLUSIONS

The paper presents the results made by electron microscopy observations of the kinematic waves of elementary step density on the vicinal growth surface near NaCl(100), formed during the motion of the pores in the crystal under the temperature gradient. It is shown that for the studied growth conditions ($T = 950$ K and $\Delta\mu/kT = 4 \cdot 10^{-3}$) the surface topography differs significantly for the <10> and <11> directions. In the

<11> direction, the vicinal surface profile is represented by monoatomic steps. Whereas in the <10> direction, as the surface curvature increases, there is a bunching of steps with the formation of macrosteps, i.e. bunches of elementary steps separated by broad areas of atomic-smooth terraces. Such a sawtooth form of the step density dependence on the longitudinal coordinate is characteristic of the shock waves described by the previously obtained particular solutions of the BE with zero boundary conditions [29]. Using the BE particular solution for the first mode and the corresponding values of the problem parameters to interpret the experimentally obtained concentration distribution (dimensionless density) of the steps, we obtained the data on the parameters of three shock waves. The values of the formation time of the observed shock waves were obtained. It was shown that with an increase in the local surface curvature and, consequently, the intensity of the diffusion-kinetic (and thermodynamic) interaction of elementary steps, the time of wave formation decreased.

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ФОРМИРОВАНИЕ УДАРНЫХ ВОЛН ПЛОТНОСТИ СТУПЕНЕЙ НА ВИЦИНАЛЬНЫХ ПОВЕРХНОСТЯХ РОСТА NaCl(100)

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Электронно-микроскопическим методом вакуумного декорирования исследована морфология поверхности роста вблизи NaCl(100), сформировавшейся при движении поры в кристалле под действием градиента температуры. Показано, что при $T = 950$ К и $\Delta\mu/kT = 4 \cdot 10^{-3}$ профиль вицинальной поверхности в направлении $\langle 11 \rangle$ представлен моноатомными ступенями, тогда как в направлении $\langle 10 \rangle$, по мере увеличения кривизны поверхности, наблюдается группирование ступеней с образованием макроступеней – сгустков элементарных ступеней, разделенных участками атомно-гладких террас. Пилообразная зависимость плотности ступеней от продольной координаты описана частным решением уравнения Бюргерса для ударной волны. Получены данные о параметрах трех ударных волн и времени их формирования.

ФОРМУВАННЯ УДАРНИХ ХВИЛЬ ГУСТИНИ СХОДИН НА ВИЦИНАЛЬНИХ ПОВЕРХНЯХ РОСТУ NaCl(100)

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Електронно-мікроскопічним методом вакуумного декорування досліджена морфологія поверхні росту поблизу NaCl(100), що сформувалася під час руху пори в кристалі під дією градієнта температури. Показано, що при $T = 950$ К і $\Delta\mu/kT = 4 \cdot 10^{-3}$ профіль віцинальної поверхні в напрямку $\langle 11 \rangle$ представлений моноатомними сходинками, тоді як у напрямку $\langle 10 \rangle$, зі збільшенням кривизни поверхні, спостерігається групування сходинок з утворенням макросходин – згустків елементарних сходинок, розділених ділянками атомно-гладких терас. Пилкоподібна залежність густини сходин від поздовжньої координати описана частинним розв'язком рівняння Бюргерса для ударної хвилі. Отримано дані про параметри трьох ударних хвиль і час їх формування.