Effect of immobile impurities on motion of steps on a vicinal face

著者	Sato Masahide
著者別表示	佐藤 正英
journal or publication title	Physical Review E - Statistical, Nonlinear, and Soft Matter Physics
volume	84
number	6
page range	61604
year	2011-12-20
URL	http://doi.org/10.24517/00028557

doi: 10.1103/PhysRevE.84.061604

Effect of immobile impurities on motion of steps on a vicinal face

Masahide Sato

Information Media Center, Kanazawa University, Kakuma-cho, Kanazawa 920-1192, Japan

(Received 5 August 2011; revised manuscript received 3 October 2011; published 20 December 2011)

We carry out Monte Carlo simulations and study the dependence of the behaviors of steps on impurities on a vicinal face. We assume that the impurities are immobile and the lifetime of them is much longer than that of adatoms. During growth, the impurities in front of a step prevent the step from advancing. If a wide terrace appears due to the fluctuations of step positions, the number of impurities on the terrace is more than other terraces. The step at the upper side of the wide terrace is slower than other steps, so that an equidistant train of steps becomes unstable. In our Monte Carlo simulations, with steps gathering and separating repeatedly, the bunches of steps are formed on the unstable surface.

DOI: [10.1103/PhysRevE.84.061604](https://doi.org/10.1103/PhysRevE.84.061604)

PACS number(s): 81.10.Aj, 81.15.Kk, 68.55.J–

I. INTRODUCTION

On a vicinal face, an array of an equidistant train of straight steps is stable in equilibrium. During growth or sublimation, however, the vicinal face becomes unstable, and the steps on the vicinal face show two types of instabilities: step wandering and step bunching. Step wandering is the instability for fluctuations along the steps and step bunching is the instability of the step distance.

One of the causes of the step instabilities is impurities attached on a surface. Cabrera and Vermilyea [1] assumed that the impurities are immobile and theoretically studied the effect of them on the motion of steps. When an advancing step collides with the impurities, which are present in front of the step, the step curves and surrounds the impurities if the distance between the impurities is longer than the diameter of the critical nucleus. Once the impurities are passed by the step and buried in a terrace, they no longer affect the motion of the step. By decreasing the distance between impurities, fluctuations along a step, which are longer than the distance between impurities, are suppressed, so that it becomes hard for the step to curve and to surround impurities and the velocity of a step decreases. When the distance between the impurities is shorter than the critical nucleus diameter, the step cannot surround the impurities and does not advance.

When impurities impinge on a vicinal face with a constant rate, the number of impurities on terraces increases with increasing the width of terraces. If wide terraces appear by fluctuations of steps, the velocities of the steps which are at the upper side of the terraces become slower than those of other steps. The decrease of the velocity of the steps causes step bunching [2–9]. Recently, Kandel and Weeks [4–6] formed a model in which the effect of the diffusion field was simplified, and studied the step bunching induced by impurities. In their model, the effect of impurities is taken into account as the low probability of advancement of step. They carried out a Monte Carlo simulation and showed that, owing to the bunching, the vicinal face is separated into large bunches and terraces without steps. In their simulations, large bunches bend and connect with each other, and a meshlike pattern of bunches is formed on the vicinal face. By using another model, Krug and co-workers [8,9] also studied the bunching induced by impurities. In one of their studies [9], they introduced a model in which the diffusion barrier around impurities is higher than

other places. They carried out Monte Carlo simulations and showed the formation of large bunches. In contradistinction to simulations by Kandel and Weeks [4–6], separation of steps from bunches and coalescence of steps to bunches repeatedly occur during bunching, and single steps exist on large terraces.

In previous studies [4–9], the form of bunches was well investigated, but two-dimensional behaviors of each step was not studied well. In this research, we carry out Monte Carlo simulations and study how the two-dimensional behaviors of steps are varied with parameters. In Sec. II, we introduce our model. In Sec. III, we show the results of simulation. In Sec. IV, we summarize the results and carry out brief discussions.

II. MODEL

The purpose of our study is to find general properties in step bunching induced by immobile impurities, so that we use a simple model. We consider a square lattice, in which the lattice constant $a = 1$. Steps are parallel to the x direction on average and the downhill direction is the y direction. The system size in the y direction is L_y and that in the x direction is L_x . We use the periodic boundary condition in the x direction and the helical boundary condition in the y direction. The steps are solid-on-solid (SOS) steps: the step positions are expressed as single-valued functions of x .

We modify the model used in previous studies [10,11]. In the model, we neglect the elastic interaction between impurities. We distinguish adatoms, impurities, solid atoms, and solid impurities. Active atoms are adatoms, impurities, solid atoms forming steps, and solid impurities forming steps. During a Monte Carlo trial, we select one active atom. If a selected atom is an adatom, an evaporation trial or a diffusion trial is carried out. The probability of evaporation of adatoms per time is $p_{\text{eva}} = 1/\tau$, where τ is the lifetime of adatoms. As a diffusion trial, we try to move an adatom to one of the nearest-neighboring sites. The hopping probability around impurities is changed complicatedly if they distort the diffusion potential. For simplicity, however, we neglect the change in hopping probability caused by impurities. The hopping probability is independent of the position of impurities and given by $1/4$ in each direction. Increase of time occurs after each diffusion trial. The increment of time is given by $\Delta t = 1/4N$, where N is the total number of adatoms. When

the selected site is already occupied by an adatom or an impurity, the selected adatom does not move and stays at the same site.

If the atom attaches to a step after a hopping trial, we successively carry out a solidification trial. In a solidification trial, we neglect the long-range interaction between steps, but forbid the formation of steps with multiple heights. The probability of solidification is given by [10,11]

$$p_s = \left[1 + \exp \left(\frac{\Delta E_s - \phi}{k_B T} \right) \right]^{-1}, \quad (1)$$

where ΔE_s is the change in step energy and ϕ is the energy gain in solidification. When impurities do not exist in a system, ΔE_s is given by $2\epsilon(2 - n_s)$, where ϵ is half of the bonding energy and n_s is the number of the nearest-neighboring solid atoms. Since we use SOS steps, $1 \leq n_s \leq 3$.

Similar to a previous model [2], we take account of two properties of impurity in our model. One is immobility of impurity: when we select an impurity as an active atom, we try evaporation or solidification without carrying out a diffusion trial. The probability of evaporation of impurities is given by αp_{eva} . In our simulation, we set α to be much smaller than unity, so that the lifetime of impurities is much longer than that of adatoms. When the selected impurity does not evaporate, a solidification trial is carried out if the impurity attaches to a step.

The second property of impurity which we take into account is the impediment of advancement of steps. To express the interruption of step advancing, we treat an impurity as an adatom which cannot connect the bonds with horizontal solid atoms. The change in step energy during the solidification of impurity is given by $\Delta E_s = 4\epsilon$, which is larger than that in a pure system. Solid impurities also affect the solidification probability in the solidification of neighboring adatoms. If the number of the nearest-neighboring solid impurities is n_i , the change in step energy during solidification of an adatom is given by $\Delta E_s = 2\epsilon(2 - n_s + n_i)$, where $1 \leq n_s + n_i \leq 3$.

When the selected atom is a solid atom or a solid impurity forming a step, a melting trial is carried out with probability [10,11]

$$p_m = \left[1 + \exp \left(\frac{\Delta E_m - \phi}{k_B T} \right) \right]^{-1}, \quad (2)$$

where ΔE_m is the change in step energy during melting. In p_s and p_m , we neglect the long-range interaction between steps and that between impurities. During solidification and melting, ϕ is a constant value, i.e., the energy gain by solidification is independent of the form of steps and the positions of impurities.

In equilibrium, the frequency of solidification is equal to that of melting at kink sites in a pure system, so that the equilibrium adatom density, c_{eq}^0 , satisfies $(1 - c_{\text{eq}}^0)p_m = c_{\text{eq}}^0 p_s$. Since $\Delta E_s = \Delta E_m = 0$ at kink sites, the equilibrium adatom density in a pure system is given by [10,11]

$$c_{\text{eq}}^0 = \frac{1}{1 + e^{\phi/k_B T}}. \quad (3)$$

The step stiffness $\tilde{\beta}$ in a pure system is given by [12]

$$\tilde{\beta} = \frac{2k_B T}{a} \sinh^2 \frac{\epsilon}{2k_B T}. \quad (4)$$

In our simulation, we impinge adatoms and impurities after a few melting, evaporation, and solidification trials. The numbers of adatoms and impurities per time are F and $p_i F$, respectively. In the simulation, we consider the condition that the impingement rate of impurities are smaller than that of adatoms, so that we set the ratio p_i to be much smaller than unity.

III. RESULTS OF SIMULATION

We first investigate how the motion of a single step changes owing to impurities. Figure 1 shows snapshots of a single step. The system size is 256×256 . The parameters we use are $\phi/k_B T = 3.0$, $\epsilon/k_B T = 2.0$, $\tau = 256$, $\alpha = 256^{-1}$, and $F = 3.0 \times 10^{-4}$. Since c_{eq}^0 in a pure system is estimated to be 4.74×10^{-2} from Eq. (2), the impingement rate under an equilibrium condition is given by $F_{\text{eq}} = c_{\text{eq}}^0/\tau = 1.8 \times 10^{-4}$. Since the impingement rate in the simulation is larger than F_{eq} , the step advances and crystal grows. In Fig. 1, white areas, a solid line, and dots on the terraces represent terraces, a step, and impurities, respectively. To compare the pattern without impurities and that with impurities, we set p_i to be 0 in Fig. 1(a) and 1.5×10^{-3} in Fig. 1(b).

Without impurities, the step is smooth with small fluctuations [Fig. 1(a)]. The step pattern changes drastically by impurities. With impurities [Fig. 1(b)], the impurities pin the step in some places and cause step wandering.

The impurities also change the step velocity. Figure 2 shows the time evolution of the average crystal height. In our simulation, we forbid the nucleation of two-dimensional islands and clustering of impurities. Since solidification occurs only at step, the crystal height increases owing to the advancement of step. We started the simulation with a clean surface, so that the impurity density is low and impediment by impurities is neglected in a very early stage ($t < 0.5 \times 10^5$). In the time interval, the growth rate of crystal in the system with impurities is as fast as that in a pure system. The density of impurities, however, increases with increasing time, so that the growth rate of crystal with impurities becomes slow in a later stage ($t > 0.5 \times 10^5$).

To study how the roughness of a step changes with impurities, we investigate the time evolution of the width of fluctuation of a step. The width is defined as [13]

$$w_s = \sum_{i=1}^{N_s} \sqrt{\frac{1}{L_x} \sum_{x_m=1}^{L_x} [y^{(i)}(x_m) - \bar{y}^{(i)}]^2}, \quad (5)$$

FIG. 1. (Color online) Snapshots of vicinal face (a) with impurities and (b) without impurities.

FIG. 2. Time evolution of average crystal height. Circles and squares show the time evolution without impingement of impurities and with $p_i = 1.5 \times 10^{-3}$, respectively

where N_s is the number of steps in one sample, $y^{(i)}(x_m)$ is the position of the i th step at $x = x_m$, and $\bar{y}^{(i)}$ is the average position of the i th step. Figure 3 shows the time evolution of w_s with various α . The data are averaged over 10 runs. In the initial stage ($t < 5 \times 10^4$), w_s linearly increases with time. Then the growth rate gradually decreases and w_s saturates in the last stage. Comparing Figs. 2 and 3, we find that the saturation of width and the change of step velocity occur simultaneously. w_s is independent of α in the initial stage, but the saturated value of them increases with increasing α . We also study dependence of w_s on p_i (Fig. 4). The width w_s is independent of p_i in the initial stage, but the saturated value of w_s increases with

FIG. 3. Time evolution of w_s with Δ : $\alpha = 128^{-1}$; $\circ$: $\alpha = 256^{-1}$; $\square$: $\alpha = 512^{-1}$. The other parameters are the same as those in Fig. 1.

FIG. 4. Time evolution of w_s with $\circ$: $p_i = 1.0 \times 10^{-3}$; Δ : $p_i = 1.5 \times 10^{-3}$; $\square$: $p_i = 2.0 \times 10^{-3}$. The other parameters are the same as those in Fig. 1.

decreasing p_i . In the initial stage, w_s is independent of both p_i and α . In the late stage of the time evolution of w_s , the decrease of p_i plays the same role as the increase of α .

Next, we carry out simulations with 64 steps and observe how the form of bunches changes during step bunching. Figures 5 and 6 show the time evolutions of step patterns during bunching. $\phi/k_B T$, $\epsilon/k_B T$, τ , α , and p_i are the same as those in Fig. 1(b). The system size is $L_x \times L_y = 512 \times 512$. The impingement rate in Fig. 5 is $F = 2.0 \times 10^{-4}$, which is smaller than that in Fig. 6, $F = 5.0 \times 10^{-4}$.

Initially, steps are equidistant and straight, and no impurity is present on the vicinal face. Since the impurities impinge with a constant rate, only a few impurities are present on terraces in the initial stage [Figs. 5(a) and 6(a)]. The step pattern in Fig. 5(a) is similar to that in Fig. 6(a): the steps are fluctuated thermally, but straight on average. Small bunches are observed in a later stage [Figs. 5(b) and 6(b)]. Since the lifetime of immobile impurities is longer than that of adatoms and solidification rate of them is lower than that of adatoms, the impurity density increases with time. If large terraces appear by fluctuations of step distances, the number of impurities on the large terraces is more than the other terraces. The steps which are in the upper side of the large terraces are slower than other steps, so that the step bunching occurs and the small bunches are formed. In the stage, the fluctuation of terrace widths becomes large with increasing the impingement rate. The difference of the step pattern owing to the difference of F appears in the last stage [Figs. 5(c) and 6(c)]. In Fig. 5(c), the bunches are long and tight, and many steps fluctuate widely and cross large terraces. On the other hand, short small bunches are formed in some places, but large long bunches are not formed in Fig. 6(c). The pattern on the vicinal face in Fig. 6(c) is similar to that in Fig. 6(b).

The cause of the step bunching is the asymmetry of impurity density. We investigate the distribution of impurity around an

FIG. 5. (Color online) Snapshots of vicinal face with $F = 2.0 \times 10^{-4}$ at (a) $t = 2.7 \times 10^3$, (b) $t = 4.2 \times 10^4$, and (c) $t = 5.8 \times 10^5$.

isolated step. Figure 7 shows the number of impurities summed in the x direction, which is defined as

$$\bar{\rho}(\Delta y) = \sum_{x_m=1}^{L_x} \rho(y - y_s(x_m)), \quad (6)$$

where $y_s(x_m)$ is the position of the step at $x = x_m$, $\Delta y = y - y_s(x_m)$ is the distance from the step, and $\rho(\Delta y)$ is the number of impurities. In Fig. 7, we use the same parameters as in Fig. 1(b). The data were averaged over 10 individual runs. If impurities attach to a step, the velocity of the step becomes slow at the position, so that the peak of the impurity number appears immediately in front of the step. Since the terrace at the lower side of the step is exposed to impurities for long time, the number of impurities is roughly equal to the

FIG. 6. (Color online) Snapshots of vicinal face with $F = 5.0 \times 10^{-4}$ at (a) $t = 2.7 \times 10^3$, (b) $t = 4.0 \times 10^4$, and (c) $t = 5.3 \times 10^5$.

equilibrium value $\bar{\rho}_{\text{eq}} = F\tau\alpha^{-1}L_x = 7.5$. On the other hand, exposure is short in the newly created part of the terrace, so that the impurity density is low behind the step.

In Fig. 7, the terrace width is so long that the gradient of impurity density is present only around the step. On the vicinal face whose terrace width is as large as that in Fig. 7, fluctuations of terrace width hardly affect the stability of steps. In Figs. 5 and 6, however, the average terrace width is $L_y/64 = 8$, which is much shorter than that in Fig. 7. Thus the effect of the fluctuations of terrace width is so large that the instability of the vicinal face occurs.

FIG. 7. Distribution of impurity density along a single step.

The initial stages of instability in Figs. 5 and 6 are explained by the above scenario, but the behavior of steps in the late stage seems to be different between Figs. 5 and 6. To find the dependence of the behaviors of steps in the late stage on parameters, we investigate the time evolution of the impurity density, w_s , and width of terrace width fluctuation, w_t , with various parameters. w_t is defined as [13]

$$w_t = \sum_{i=1}^{N_s} \sqrt{\frac{1}{L_x} \sum_{x_m=1}^{L_x} [l^{(i)}(x_m) - \bar{l}]^2}, \quad (7)$$

where $l^{(i)}(x_m) = y^{(i+1)}(x_m) - y^{(i)}(x_m)$ and $\bar{l}$ is the average terrace width. Since we use a helical boundary condition in the y direction, $y^{(n_s+1)}(x_m) = y^{(1)}(x_m) + L_y$.

Experimentally, the impingement rate of atoms and impurities may be controlled more easily than the other parameters, so that we first investigate how time evolutions are varied by p_i . Figure 8 shows the time evolution of the average impurity density ρ_i with various p_i . In the initial stage, ρ_i increases linearly with time. Then the growth rate becomes gradual, and ρ_i saturates in the last stage. The saturated value of ρ_i seems to

FIG. 8. Time evolutions of impurity density with various p_i . $\square$: $p_i = 2.0 \times 10^{-3}$; $\circ$: $p_i = 1.5 \times 10^{-3}$; $\diamond$: $p_i = 1.0 \times 10^{-3}$; $\triangle$: $p_i = 0.5 \times 10^{-3}$. The saturated values of ρ_i in the last stage are given by 2.1×10^{-2} with $p_i = 2.0 \times 10^{-3}$, 1.5×10^{-2} with $p_i = 1.5 \times 10^{-3}$, 9.8×10^{-3} with $p_i = 1.0 \times 10^{-3}$, and 5.1×10^{-3} with $p_i = 0.5 \times 10^{-3}$.

FIG. 9. Time evolutions of width of the fluctuation of terrace width with various p_i . The marks are the same as those in Fig. 8. In the last stage, w_t increases with a power law. The exponent of the power-law growth, γ_t , is given by $\gamma_t = 2.5 \times 10^{-2}$ with $p_i = 2.0 \times 10^{-3}$, $\gamma_t = 2.0 \times 10^{-2}$ with $p_i = 1.5 \times 10^{-3}$, $\gamma_t = 1.5 \times 10^{-2}$ with $p_i = 1.0 \times 10^{-3}$, and $\gamma_t = 1.0 \times 10^{-2}$ with $p_i = 1.0 \times 10^{-3}$.

increase proportionally to p_i . Figures 9 and 10 show the time evolutions of w_s and w_t with various p_i , respectively. The widths grow rapidly in an early stage. Then they grow with power law in a later stage. The exponent of the power-law growth of the terrace width is smaller than that of the step width, and both of them increase gradually with increasing of the ratio of impingement of impurity, p_i .

We also investigate the time dependence of ρ_i , w_t , and w_s on F . Figure 11 shows the dependence of the time evolution of ρ_i on F . In the initial stage, ρ_i increases rapidly with time. In the time interval, the dependence of the time

FIG. 10. Time evolutions of width of fluctuation of steps with various p_i . The marks are the same as those in Fig. 8. The exponents of the power-law growth in the last stage are given by $\gamma_s = 3.0 \times 10^{-2}$ with $p_i = 2.0 \times 10^{-3}$, $\gamma_s = 2.5 \times 10^{-2}$ with $p_i = 1.5 \times 10^{-3}$, $\gamma_s = 2.0 \times 10^{-2}$ with $p_i = 1.0 \times 10^{-3}$, and $\gamma_s = 1.5 \times 10^{-2}$ with $p_i = 1.0 \times 10^{-3}$.

FIG. 11. Time evolution of impurity density with various F . Δ : $F = 3.0 \times 10^{-4}$; $\square$: $F = 3.5 \times 10^{-4}$; $\circ$: $F = 4.0 \times 10^{-4}$; $\diamond$: $F = 5.0 \times 10^{-4}$. The saturated values of ρ_i in the last stage are 8.4×10^{-3} with $F = 3.0 \times 10^{-4}$, 6.6×10^{-3} with $F = 3.5 \times 10^{-4}$, 5.6×10^{-3} with $F = 4.0 \times 10^{-4}$, and 4.8×10^{-3} with $F = 5.0 \times 10^{-4}$.

evolution on F seems to be small. ρ_i saturates in the last stage. With increasing impingement rate, the saturated value decreases and the saturation occurs early. Figure 12 shows the time evolution of w_t with various impingement rates. The saturation of w_t , which appears in the last stage, occurs early with increasing the impingement rate. The saturated value decreases with increasing F . With $F = 3.0 \times 10^{-4}$, we can find a power-law growth of w_t before the saturation occurs. The exponent of the power-law growth is 0.20, which is similar to that in Fig. 9. With other F , the time interval with power-law growth is not found clearly. Figure 13 shows the time dependence of w_s with various F . Saturation of w_s occurs in the last stage when $F > 3.5 \times 10^{-4}$. The saturated value decreases with increasing F , which is similar to the saturation of w_t . The saturation of w_s occurs more slowly than that of w_t . When the impingement rates are larger than

FIG. 12. Time evolutions of width of fluctuation of step distances. The marks are the same as those in Fig. 11.

FIG. 13. Time evolutions of width of fluctuation of steps. The marks are the same as those in Fig. 11.

3.0×10^{-4} , w_s grows gradually before saturation and we cannot observe the power-law growth clearly. On the other hand, with $F = 3.0 \times 10^{-4}$, which is the lowest impingement rate in our simulation, the saturation does not occur. The width keeps growing with a power law. The exponent is 0.25, which is equal to the exponent we obtained in Fig. 10.

IV. SUMMARY AND DISCUSSIONS

In this paper, we studied the effects of immobile impurity on motions of steps on a vicinal face. We introduced a model that takes account of two properties of impurity. The impurities do not move on the vicinal face and prevent the step from advancing. By carrying out Monte Carlo simulations, we found that both step wandering and step bunching occur during growth, owing to the pinning by impurities.

In the initial stage of the step wandering, w_s of an isolated step linearly increases with time. In the time interval, the value of w_s is independent of α and p_i . w_s is saturated in the last stage. The saturated value of w_s becomes larger with larger α and smaller p_i . Since the wandering is induced by the pinning caused by impurities, the relation between w_s and p_i obtained from our simulation seems to be the opposite. The opposite relation may be caused by the change of step velocity due to impurity on w_s . In our simulation, the step velocity decreases with increasing p_i , although the saturated value of w_s increases with increasing the step velocity in other systems [10,14,15]. Thus, to investigate the relation between w_s and p_i , we need to take account of the change of step velocity induced by impurity on w_s in detail. When the step wanders widely, overhanging of steps, which has been neglected in our model, frequently occurs. Thus we intend to study the relation between w_s and p_i in detail with a non-solid-on-solid model.

In our simulation, the form of bunches varies with the impingement rate of adatoms and impurities. When the impingement rate of the adatoms is small, the velocities of steps are slow. The surface is exposed to the vapor phase for a long interval, so that a lot of impurities accumulate on a vicinal face and the effect of impurity becomes large. Thus

large long bunches were formed in our simulation. With a large impingement rate, the steps on the vicinal face advance fast. The time interval that a terrace is exposed to the vapor phase is short, so that few impurities accumulate on the vicinal face. Some impurities act as pins, but the effect is weak and large bunches are not formed. Short bunches with a few steps are formed by pinning and modulation of step density is observed on the surface.

In the last stage, the saturation of the widths w_s and w_t was observed in Figs. 12 and 13, but the widths do not saturate in Figs. 9 and 10. Comparing the time at which saturation occurs in Fig. 11 with that in Figs. 12 and 13, we find that the impurity density saturates faster than the widths w_s and w_t . Thus, if we carry out simulation for a longer time with large p_i and small F , we can observe the saturation of the widths after a long interval of power-law growth.

In our simulation, steps crossing large terraces were observed. Existence of the steps on large terraces means that separation and collision between steps and bunches occurs

frequently during bunching. The result is similar to that in Vollmer's model [9], but different from that of Week's model [4–6]. One of the main differences between our model and Week's model is the treatment of the diffusion field of adatoms. In our model and Vollmer's model, the surface diffusion of each adatom is taken into account, but in Week's model [4–6], the diffusion field is simplified. The difference may cause the difference in the step motion. In our model, we consider a simple model in which the impurities are immobile. Now we intend to study how the motion of steps changes with the mobility of adatoms.

ACKNOWLEDGMENTS

This work is supported by Grants-in-Aid for Scientific Research from Japan Society for the Promotion of Science, and some parts of this study was carried out under the Joint Research Program of the Institute of Low Temperature Science, Hokkaido University.

-
- [1] N. Cabrera and D. A. Vermilyea, in *Growth and Perfection of Crystals*, edited by R. H. Doremus, B. W. Roberts, and D. Turnbull (Wiley & Sons, New York, 1958), p. 393.
 - [2] F. C. Frank, in *Growth and Perfection of Crystals*, edited by R. H. Doremus, B. W. Roberts, and D. Turnbull (Wiley & Sons, New York, 1958), p. 411.
 - [3] J. P. van der Eerden and H. Müller-Krumbhaar, *Phys. Rev. Lett.* **57**, 2431 (1986).
 - [4] D. Kandel and J. D. Weeks, *Phys. Rev. B* **49**, 5554 (1994).
 - [5] D. Kandel and J. D. Weeks, *Phys. Rev. Lett.* **72**, 1678 (1994).
 - [6] D. Kandel and J. D. Weeks, *Phys. Rev. B* **52**, 2154 (1995).
 - [7] L. A. N. Amaral and J. Krug, *Phys. Rev. E* **55**, 7785 (1997).
 - [8] J. Krug, *Europhys. Lett.* **60**, 788 (2002).
 - [9] J. Vollmer, J. Hegedüs, F. Grosse, and J. Krug, *New J. Phys.* **10**, 053017 (2008).
 - [10] Y. Saito and M. Uwaha, *Phys. Rev. B* **49**, 10677 (1994).
 - [11] M. Sato, M. Uwaha, and Y. Saito, *Phys. Rev. Lett.* **80**, 4233 (1998).
 - [12] Y. Saito, *Statistical Physics of Crystal Growth* (World Scientific, Singapore, 1996).
 - [13] M. Sato, *J. Phys. Soc. Jpn.* **80**, 074604 (2011).
 - [14] I. Bena, C. Misbah, and A. Valance, *Phys. Rev. B* **47**, 7408 (1993).
 - [15] M. Sato and M. Uwaha, *J. Phys. Soc. Jpn.* **65**, 2146 (1996).