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Competitive deposition–evaporation growth models

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HIGHLIGHTS

- It is shown that the scaling behaviour of the standard BD and RDSR models are independent of particle evaporation.
- Two power law relations have been found in terms of probability for the BD/RE model.
- By rescaling the data corresponding to the BD/RE model, a fine agreement with the relation introduced by Chou et al. is experienced.

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ABSTRACT

We study two models for competitive deposition and evaporation of particles from rough surfaces. The process of deposition is carried out for two models, one according to the ballistic deposition (BD) and the other according to the random deposition with a surface relaxation (RDSR). The process of evaporation is the same for both models, where it obeys the random evaporation model (RE). The probability of the deposition and evaporation is $1 - p$ and p, respectively. We show that the scaling behaviour of the standard BD and RDSR models are independent of particle evaporation. Particle evaporation only causes a delay for the scaling behaviour of the models. This delay is independent of the surface size for all typical probabilities and depends only on the value of p. We obtain two power law relations in terms of p for the BD/RE model. One of these relations is derived from the ratio of the crossover times, which is the ratio of the time of surface saturation to the transient time from RD to BD (t_2/t_1), and the other relation comes from the ratio of the surface roughness (W_2) observed in time t_2 to the surface roughness (W_1) in time t_1. By rescaling the data corresponding to the BD/RE model, a fine agreement with the relation introduced by Chou et al. is experienced.

1. Introduction

The ability to characterise the spatial and temporal behaviour of the growth process of surfaces and interfaces has proved to be an important issue in the context of thin films [1], multilayer films [2] and biological surfaces [3,4]. Gaining knowledge about the behaviour of surface roughness in all stages of the growth process may help one to control electrical, magnetic and optical properties of the surfaces and interfaces. This also enables study of the crucial parameters involved in the establishment of the surface [5–7].

As understood in all scientific branches, in order to fully study an observed process, in addition to the analytical approach a numerical technique needs to be implemented. This enables the study and comparison of the dominant factors of each process (see Refs. [8–10]). These factors which influence the primary processes (absorption, diffusion and evaporation) depend on the conditions of the experiments and the particle–surface interactions [6]. Temperature [9,11] is the main factor

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having an effect on diffusion and evaporation from surfaces (see Refs. [6,12]). For typical growth temperatures, sometimes the evaporation process is ignored. Some examples in this case are growth processes in application to various surfaces, for example, for Si [13,14] and GaAs growth [15,16]. However, in some cases neglecting the evaporation process is not an option, see for example, Ref. [17].

The fact that higher temperatures cause the particles to diffuse on the surface in a longer length scale with a higher evaporation probability [18] motivates the study of various aspects of the evaporation process. Hence, in this work we consider an ideal model while ignoring the diffusion effects in order to study the efficiency of evaporation. In this context, Karunasiri et al. [19] in $(1 + 1)$ dimensions and Yao et al. [20] in $(2 + 1)$ dimensions developed an equation enabling the consideration of evaporation. Some of the well-known discrete models which focus on the microscopic details of surface growth are the random deposition (RD) [21], the random deposition with surface relaxation (RDSR) [22], the ballistic deposition (BD) [22,23] and the restricted solid on solid (RSOS) [24] models. In contrast to discrete models, continuous models focus on macroscopic details of surface growth, for example, Edward–Wilkinson (EW) [25]

$$\frac{\partial h(x,t)}{\partial t} = \upsilon \nabla^2 h(x,t) + \eta(x,t),$$

and Kardar–Parisi–Zhang (KPZ) [26]

$$\frac{\partial h(x,t)}{\partial t} = \upsilon \nabla^2 h(x,t) + \lambda(\nabla h(x,t))^2 + \eta(x,t),$$

where υ and λ are the surface tension and velocity, respectively. The EW is a linear equation that describes diffusion of deposited particles on a surface during growth processes where the KPZ is a non-linear equation which explains surface fluctuations of rough surfaces. Note that $\eta(x,t)$ is a Gaussian white noise with a zero mean and $\langle \eta(x,t)\eta(x',t')\rangle = 2D\delta(x-x')\delta(t-t')$.

Family and Vicsek [27] introduced three scaling exponents to study the spatio-temporal scale invariant behaviours of rough surfaces. They described a surface by a set of particles which were placed at the highest position $h(i,t)$ on sites represented by i at time t. Taking into account periodic boundary conditions during the growth, the root mean square (rms) roughness $W(L,t)$ is defined by $W(L,t) = \sqrt{\frac{1}{L}\sum_{i=1}^{L}[h(i,t) - \langle h(t)\rangle]^2}$, where, $\langle h(t)\rangle$ is the average height of the surface at time t. Furthermore, Family and Vicsek showed that for $t \ll t_{sat}$ the rms roughness would be $W \approx t^{\beta}$, and for $t \gg t_{sat}$ the rms roughness would be $W \approx L^{\alpha}$. Further, it is assumed that $t_{sat} \approx L^{Z}$, where t_{sat} is a crossover time that indicates when the surface roughness obtains a saturated value. Note that the parameters β, α and $Z = \alpha/\beta$ are the growth, roughness and dynamic exponents, respectively. In addition, the scaling function of rms roughness can be written as $W(L,t) \approx L^{\alpha} f(\frac{t}{L^{Z}})$. Note that models with the same scaling exponent lie in the same universality classes [6,7] The BD and RSOS models are included in the KPZ class while the RDSR model belongs to the EW class.

In many real surface growth processes, a competitive mechanism may take place. Therefore, the dynamics of competitive models which are more realistic have been continuously studied [28–39]. Most simulations include deposition of more than one kind of particles in different growth mechanisms. This is due to various interactions between particles. For example, Horowitz et al. introduced various competitive models, generically called X-RD [34–36]. The X-models include some well-known depositing models. This means that the X-correlated model comes into play when the probability is p and the RD model comes into play when the probability is $1 - p$. They numerically found a dynamic scaling ansatz that showed the p dependence of $W(L,t,p)$ as

$$W(L,t,p) : L^{\alpha_{\diamond}} p^{-\delta} F\left(\frac{t}{L^{Z_{\diamond}} p^{-y}}\right), \tag{1}$$

and found a scaling relationship between the exponents, where '$\diamond$' refers to the X-model. Note that δ and y are two new scaling exponents. Braunstein et al. [37] introduced a new model as constrained EW (CEW) and studied a competitive growth process CEW-RD, where particles deposit by the rule of CEW with probability p. They showed that as p varies from 0 to 1, a transition from the KPZ to the EW class is observed. They derived coefficients for the KPZ equation analytically using the BD-RD and CEW-RD models at small and large probabilities as a power function of p. Oliveira et al. [38] by considering the RSOS model, introduced a competitive model involving deposition and evaporation of particles with probability p and $1-p$, respectively. They found a power law relation for the crossover time from the EW to the KPZ model that had an excellent agreement with theoretical calculations. For these special systems, with two different crossover points, Chou et al. [39] presented a new parameter-free scaling relation by using values of the roughness widths in the crossover times.

In order to understand the effects of evaporation on the morphology of a surface, we study effects of deposition and evaporation of particles on surfaces competitively. Two lattices are considered with the same kind of particles; the particles can evaporate from both surfaces with the probability of p as in the RE model, and deposit on both surfaces with the probability $1 - p$ but with different models. For one surface, the deposition obeys the BD model and for the other surface it obeys the RDSR model. In our simulations, we have two regimes with different scaling behaviours before the surface saturates to a fixed roughness width. We find a relation for important surface parameters in terms of the probability p. In addition, we check the validity of the new scaling relation which was introduced by Chou et al. [39] Our work is organised as follows: the methods of surface growth are discussed in detail in the second section; numerical simulations, scaling exponents are stated and conclusions are discussed in the third section.