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Trends and perspectives in solid-state wetting / Mouillage solide–solide : tendances et perspectives

Trends and perspectives in solid-state wetting

In our daily life we experience the wetting behavior of liquids. As an example, under the rain, droplets form spherical caps on windows, and different cloths may either stay dry via the beading and rolling of water droplets, or become wet via imbibition. Although sensed since the antiquity, wetting concepts have been precisely defined in the nineteenth century by Thomas Young and Athanase Dupré.

During the 20th century, these concepts were transferred to the study of nanoscale solids, notably by the Bulgarian school with Ivan N. Stranski, Rostislaw Kaischew, and others. The study of solid-state wetting provided a rationale for the observation of different growth modes of thin solid films, leading sometimes to continuous films, and sometimes to assemblies of solid "droplets".

Nowadays, while epitaxial growth is still a central tool to obtain thin films and nanoparticles on solid substrates, novel ways to produce nanoscale solids at solid surfaces are known, such as nanoscale lithography, nanoparticle deposition, catalyzed nanowire growth, or wafer bonding. These techniques allow one to produce a wide variety of nano-objects (islands, wires, films, etc.), which evolve under annealing while interacting with the substrate following laws that can once again be understood with the help of the concepts of wetting. However, the wetting behavior of solids is different from that of liquids because it involves different physical ingredients such as elastic strain, anisotropy, and mass transport via the diffusion of surface atoms. The aim of this volume is to provide a wide (but non-exhaustive) overview of solid-state wetting, focusing both on basic concepts and on novel trends.

The issue begins with a review of the wetting of solid helium crystals on solid walls by Sébastien Balibar. In this article, solid helium is shown to be a model system for many properties of more "usual" condensed matter. Indeed, since most of its wetting properties are unaffected by quantum coherence, solid helium essentially behaves as a classical solid. Then, as an experimental system, helium cumulates two important advantages: (i) macroscopic centimeter-scale crystals can be grown and visualized by optical techniques; (ii) solid helium exhibits a very fast shape relaxation. Therefore, solid helium allows one to study fundamental wetting properties such as the equilibrium contact angle, or advancing and receding contact angles.

In the second paper, Francesco Montalenti et al. present another model system that has been the subject of a large literature: SiGe growth. The global picture that arises from the literature indicates that, after the formation of a wetting layer, islands appear. Their shape is governed by a balance between a gain in mismatch strain energy and a surface energy cost. This balance results in island shapes with an increasing height-to-base ratio as their volume increases. The authors show that this global picture should be considered carefully, and point out that other ingredients are relevant, such as low-energy (105) facets and edge energies, which lead to the formation of wires with a selected width.

Then comes a series of four papers on solid-state dewetting (also called agglomeration). Dewetting is the process by which a film destabilizes to form islands (or droplets) in order to reduce its energy. This process has been the subject of a large literature in the case of liquid films. Experiments of solid-state dewetting have also been reported for several decades. However, carefully controlled experiments have been performed recently, allowing a precise comparison with theoretical models.

One of the major open questions in dewetting is the role of crystalline anisotropy. The first two papers present models which account for singular anisotropy, i.e. for the presence of facets. However, the two approaches are very different: while Anna Chame et al. start from a microscopic description of facets, including two-dimensional nucleation, Rachel V. Zucker et al. propose a macroscopic phenomenological picture for the motion of the facets. While both types of modeling have been validated by the comparison to microscopic simulations (kinetic Monte Carlo) or to experiments, there is still work in my opinion to understand their respective domains of validity. The two types of modeling agree on some results, such as the absence of thinning of the film behind the dewetting rim when the film exhibits a faceted orientation parallel to the substrate, but they also exhibit differences, e.g., in the time-dependence of the velocity of dewetting fronts. In addition, these models suggest novel phenomena, such as layer-by-layer dewetting or monolayer dewetting in the paper of A. Chame et al.

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The next paper in this series, from Fabien Cheynis et al., reports on the dewetting of monocrystalline Si(001) and Ge(001) on amorphous SiO_2. These experiments lead to a number of observations, e.g., the top of the dewetting rim is faceted, and the rim height increases in a layer-by-layer fashion. In addition, Si and Ge exhibit different fingering morphologies resulting from the dewetting front instability. Finally, ultra-thin films seem to exhibit a different behavior, with fractal-like morphologies.

The last paper in the dewetting series is devoted to an experimental analysis of the evolution of the global film morphology during the dewetting of polycrystalline Pt films on yttria-stabilized zirconia substrates, by Henning Galinsky et al. These authors use Minkowski functionals to characterize the film morphology, and propose to model the evolution of the morphology by means of a cellular automaton model based on a discretization of the time-dependent Ginzburg–Landau equation.

Interestingly, these contributions on dewetting provide different answers to a basic question: what is the evolution of the diameter of a hole in a film as a function of time? In our opinion, this is an important open issue that still needs to be clarified.

The following contribution, by Koichi Sudoh et al., reports on the experimental observation of reactive wetting of Si(001) films on amorphous SiO_2 during and after the dewetting process. The Si film and islands indeed leave "footprints" along the triple line on the SiO_2 substrate, which are attributed to an interfacial reaction. The rate-limiting process is discussed in the light of experimental measurement of the activation energy of the deepening of the trenches observed along the triple line.

Surface electromigration, the drift of mobile surface atoms in the presence of electric currents, is known as a major origin of breakdown of micro and nanoscale devices. Indeed, it triggers morphological instabilities of the surface. In the next manuscript, Mikhail Khenner discusses the effect of substrate wetting on electromigration-induced thin film instabilities. This is, in my opinion, an interesting perspective to control the dewetting process discussed in the above-mentioned contributions.

Beyond dewetting, another well-studied liquid wetting phenomenon is the so-called Lotus effect, by which a liquid drop does not wet and may roll on plant leaves, thereby contributing to the cleaning of the leaves. This effect is due to the existence of a wetting state where the liquid floats on the top of the topographical micro-structure of the leaves, keeping an air cushion between the liquid and the bottom of the structures. A similar effect has actually been observed for the wetting of nanoscale solids on nanopillars. This effect – and others such as imbibition – related to the wetting of solids on nanopatterned substrates, are modeled in the contribution of Yukio Saito et al. The stability and the dynamics of several wetting states are discussed. Then, epitaxial growth on these surfaces is analyzed.

Finally, we come back to our leitmotiv, the analogy with liquids. The last contribution is a report from Michael J. Davis et al. on the dynamics of liquid droplet spreading. The aim of this contribution is to point out a problem which, to my knowledge, has not been addressed in the case solid-state wetting, and which therefore provides hints for future research on solid-state wetting.

As will become clear for the reader of this volume, there are still many open issues in the understanding of solid-state wetting. In addition, these questions have some technological relevance, since the stability of the morphology of nanostructures is crucial for many applications. Thus, we expect that this research field will remain very active in the future.

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