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Critical Review

Strategies for the growth of large-scale self-organized structures

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ABSTRACT

Nanostructured surfaces are of fundamental importance in an ever-increasing number of applications. Strategies based on self-organization are a promising route for the controlled fabrication of nanostructured objects. Indeed, self-organization appears to be a much more frequent behavior than presumed and could be seen as a rule more than an exception. Nevertheless, in order to be practical and usable, the ability to tailor the size and dimensionality of the grown nanostructures is a prerequisite. This involves a full understanding of the fundamental aspects controlling self-organization mechanism.

The parameters governing the growth of self-organized surfaces are not yet fully understood. This may explain why their use is still limited. This review discusses a prototypical self-organized surface, namely, the O/Cu(110)-(2 × 1) surface and identifies the parameters which control the self-organization process and how they can be tuned. It is shown how these parameters can be varied by controlled co-adsorption of species at the surface in order to tailor the self-organization process and extend the range of achievable nanostructures.

1. Introduction

In his famous lecture *There's Plenty of Room at the Bottom* [1], presented on December 29th, 1959 at the annual meeting of the American Physical Society at Caltech, Richard P. Feynman kicked off a new field of research, which came to be called Nanoscience, and that led to a tremendous amount of applications that extend far beyond the area of physics. By answering some apparently naive questions, Feynman managed to introduce the manipulation and control of nanometer scale objects and predicted how domains such as data storage, microscopy, computer science, chemistry, biology, and health may benefit from it. A rapidly developing field reaching toward nanoscale limits is microelectronics.

Indeed, the microelectronic industry evolved since its early times to become an essential component of our everyday life. However, it recently achieved a turning point with a major change in paradigm. For half a century, it has followed the Moore's law [2] which states that the processing power doubles every two years. With time, the Moore's prediction changed to an objective to be fulfilled by the industry, but for the first time the international consortium in charge of the definition of the roadmap announced that the Moore's law will not be the core of the research and development plans anymore [3]. This is not the consequence of a technical impossibility, but a considered decision of the industry which is aimed at finding new ways to produce devices, associated with a rethinking of performance scaling. This major change in the way the industry conceives now the future of the domain is often referred to as “more than Moore”.

In recent years, the development of mobile technology has increased the demand for specialized, low-power microchips. In the past, only a few different microprocessors could be produced in huge quantities, but now the number of specific microchips has significantly grown to fulfill more and more applications. This has implications in the politics of production which could switch from mass to on-demand production. A major challenge for custom chips is to find versatile methods of fabrication at reduced design costs. Photolithography has reached such a high degree of complexity that its evolution is now limited by its own progress [4]. Even, the very expensive development of extreme ultraviolet lithography, although adapted to mass production of integrated circuits, lacks flexibility needed for new kind of devices. New low-cost, high throughput and adaptable manufacturing methods are therefore necessary in order to move to the next step of development of microelectronics.

In this context, a bottom-up approach based on self-organization, more versatile than traditional photolithography-based top-down methods, is a reasonable alternative [5] and may be considered as the only viable approach. In particular, self-organized surfaces may be used as templates for epitaxial growth and may benefit emerging fields such as molecular electronics based on organic semiconducting materials [6].

The production of stable, well-controlled nanostructured surfaces with specific properties is not only essential for the development of the microelectronics industry, but is also a requirement in many domains

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such as catalysis, photonics, sensor design, photovoltaics, and biomedical science. Beyond that, nanostructures represent a field for innovation due to the novel properties that emerge from size reduction associated with low dimensionality.

This review is organized as follows. In Section 2, the self-organization phenomenon is discussed, and its ubiquity is demonstrated. The focus is on stress-induced surface nanostructuring and how it can be used as a template for growth of nanostructured materials. Section 3, is dedicated to a short introduction to the theory of elasticity and to the basic concepts that are necessary to understand the effect of surface stress on self-organization. In Section 4, the O/Cu(110)-(2 × 1) surface, which can be seen as a prototype of periodic self-organized nanostructured surfaces, is described and the role of the parameters that are at the origin of the self-organization is explained. The conclusions drawn on this surface may be extended to the other stress-induced self-organized surfaces. A promising route for tunable self-organized surfaces is reported in Section 5 and results are shown on how characteristic sizes on the O/Cu(110)-(2 × 1) surface can be adjusted by sulfur co-adsorption. Examples of applications of such a highly tunable nanostructured self-organized surface are given in Section 6. Finally, conclusions and prospects are summarized in Section 7.

2. Self-organization

Self-organization is present everywhere from fundamental physics [7] to biology [8] and at every size scale from nanoscopic to astronomical (see Fig. 1). In nature, self-organization is a rule more than an exception. It is a fundamental component that shapes our universe from the very beginning. It is at the origin of the birth of the first stars [9] and dominates galaxy formation in both space and time [10,11]. In association with self-similarity, it is believed to be an essential component of the appearance of life [12,13] and of all the shapes found in nature [14]. Its influence has been shown in the animal, vegetal and mineral world and is responsible for, as examples, the stripes patterns of zebras [8], the fairy circles [15] and vegetation arrangements [16], and the formation of structures in sand [17,18].

The term 'self-organization' is probably the most general one that was used, in many contexts, to describe the above behaviors. In order to reflect this wide usage, self-organization will be defined here, in its broader sense, as the natural tendency to form organized structures. Although it is often used to refer to dissipative systems associated with non-equilibrium states [20–23], it should not be restricted to this unique area. In the present case, another kind of self-organization, that appears at equilibrium and is the result of energy minimization, will be considered. 'Self-assembly' also refers to self-organized systems at equilibrium, however its use will be limited here to molecular self-organization in which interactions between molecules are essential. This review, will mainly focus on the self-organization resulting from the self-organized growth on surfaces which leads to periodic, or self-ordered, nanostructures.

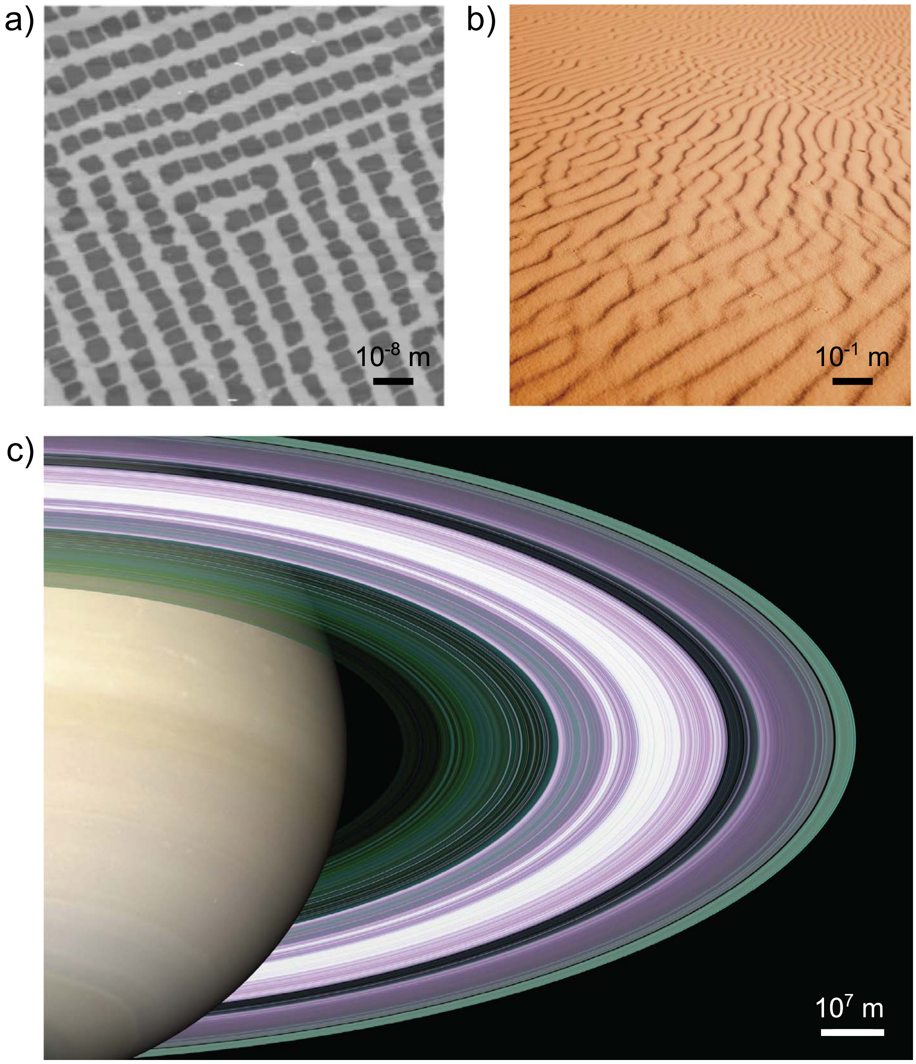

Fig. 1. Self-organization appears at all length scales. a) Nanoscopic scale: The adsorption of atomic N on the surface of Cu(110) [19], b) macroscopic scale: wind-induced patterns in sand (image Creative Commons), c) astronomical scale: the rings of Saturn exhibit complex patterns that are the result of the interplay between the gravitational forces of the planet and its satellites (Courtesy NASA/JPL-Caltech).