C. R. Physique 16 (2015) 741–757

Contents lists available at ScienceDirect

Comptes Rendus Physique

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Prix Gustave-Ribaud 2014 de l'Académie des sciences

Instability-driven quantum dots

Instabilité et boîtes quantiques

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ARTICLE INFO

Article history:
Available online 4 September 2015

Keywords:
Strained film
Morphological instability
Epitaxy

ABSTRACT

When a film is strained in two dimensions, it can relax by developing a corrugation in the third dimension. We review here the resulting morphological instability that occurs by surface diffusion, called the Asaro–Tiller–Grinfel'd instability (ATG), especially on the paradigmatic silicon/germanium system. The instability is dictated by the balance between the elastic relaxation induced by the morphological evolution, and its surface energy cost. We focus here on its development at the nanoscales in epitaxial systems when a crystal film is coherently deposited on a substrate with a different lattice parameter, thence inducing epitaxial stresses. It eventually leads to the self-organization of quantum dots whose localization is dictated by the instability long-time dynamics. In these systems, new effects, such as film/substrate wetting or crystalline anisotropy, come into play and lead to a variety of behaviors.

RÉSUMÉ

Un film qui subit une pression selon deux dimensions peut relaxer cette contrainte en ondulant dans la troisième dimension. Nous analysons ici l'instabilité morphologique qui en résulte grâce à la diffusion de surface, l'instabilité d'Asaro–Tiller–Grinfel'd (ATG), en particulier sur le système paradigmatique silicium/germanium. L'instabilité est régie par l'équilibre entre la relaxation élastique liée à l'évolution de la surface, et son coût en énergie de surface. Nous nous focalisons ici sur sa manifestation aux échelles nanométriques dans les systèmes épitaxiés, quand un film cristallin est déposé sur un substrat de paramètre de maille différent, induisant une contrainte élastique bi-axiale. Cette évolution débouche aux temps longs sur l'auto-organisation de boites quantiques dont la localisation est dictée par la dynamique aux temps longs. Dans ces systèmes, des nouveaux effets entrent en jeu, comme le mouillage entre le film et son substrat ou l'anisotropie cristalline, et débouchent sur une diversité de comportements nouveaux.

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http://dx.doi.org/10.1016/j.crhy.2015.08.002
1631-0705/

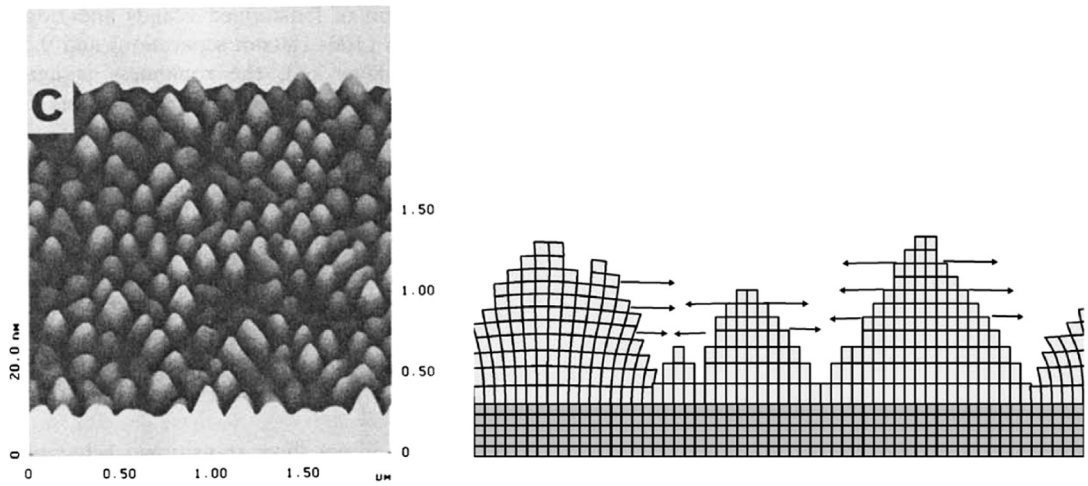

Fig. 1. Seminal observation of the ATG instability on SiGe [14] and schematic representation of the strain relaxation allowed by a morphological evolution, from [18].

1. Introduction

Quantum dots are nowadays common objects, easy to fabricate, manipulate and use on an everyday laboratory life basis. These objects, which keep charge carriers in a structure with dimensions smaller or of the order of the de Broglie wavelength, exhibit quantum confinement effects. After the technological revolution introduced by the transistor in the late 1940s, which resulted in our information-based societies, the development of such quantum confining nanostructures contain the seeds of strong technologic and scientific progress [1–3] (and references therein).

The first quantum nanostructures to be proposed and realized are quantum wells that confine charge carriers in one dimension and led to the 2000 Nobel Prize awarded to Alferov and Kroemer [4,5]. They found many applications in laser diodes for, e.g., compact disc readers or fiber optic transmitters, and more recently in the blue laser diodes that led to the 2014 Nobel Prize awarded to Akasaki, Amano and Nakamura [6]. In a 'quantum wire', such as a carbon nanotube, electrons are confined in two dimensions, but are free to move in one direction; in a 'quantum dot' or 'artificial atom', electrons are confined in all directions, which leads to a discrete energy spectrum. Quantum dots are thence used in labs for producing single photons and entangled photons, quantum computing devices, single-electron transistors, and are even already embedded in television displays first commercialized in 2013.

Quantum dots (QD) may be produced with different techniques, in colloidal solutions or in semiconductor epitaxy. If lithography is used in relatively large structures, the control of crystal growth down to a few nanometers allows the in-situ self-organization of defect-free nanostructures when a thin film is coherently deposited on a substrate. This growth exemplifies the general trend towards self-organization in out-of-equilibrium systems, which is commonly associated with the so-called Stranski–Krastanov growth, specific to epitaxial systems and explained in the following. Its driving force is the relaxation of the stress induced by the lattice mismatch between a film and its substrate, while it is hindered by the surface energy cost and by wetting effects between a film and a substrate. At the temperatures where QD grow, only surface mass transfers are activated and lead to surface corrugation. This evolution should thence not be confused with the buckling of a strained film, which involves the movement of the full system.

In some growth conditions, QD growth occurs without nucleation and results from a morphological instability, the ATG instability, proposed by Asaro and Tiller [7] and then Grinfel'd [8]. It was experimentally demonstrated in ^{4}He films in Balibar's group [9–11], and also in polymer films [12]. In semi-conductors' epitaxy, it was evidenced in indium–gallium–arsenic systems [13] and in silicium–germanium (SiGe) films [14,15]. However, QDs result mostly in the long-time dynamics of the instability, where numerous effects come into play, especially wetting interactions between the film and its substrate, crystalline anisotropy, but also non-linear effects. The goal of the present article is to review the different results that may be drawn theoretically for this instability, and to compare them with experimental knowledge.

2. Asaro–Tiller–Grinfel'd instability

The Asaro–Tiller–Grinfel'd instability occurs when a strained film relaxes by developing a surface corrugation, see, e.g., [16,17] for a review and Fig. 1. In hetero-epitaxial systems, strain occurs when a film is coherently deposited on a substrate with a different lattice parameter. Hence, the film experiences a bi-dimensional strain in the substrate plane that already leads to a Poisson dilatation in the growth direction. The morphological evolution then happens via surface diffusion driven by elastic relaxation. The description of the ATG instability is merely ruled by surface diffusion enforced by the surface chemical potential density μ that includes capillary and elastic effects. We consider a regular film surface lo-