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Self-organized nanopatterning of silicon surfaces by ion beam sputtering

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ABSTRACT

In recent years Ion Beam Sputtering (IBS) has revealed itself as a powerful technique to induce surface nanopatterns with a large number of potential applications. These structures are produced in rather short processing times and over relatively large areas, for a wide range of materials, such as metals, insulators, and semiconductors. In particular, silicon has become a paradigmatic system due to its technological relevance, as well as to its mono-elemental nature, wide availability, and production with extreme flatness. Thus, this review focuses on the IBS nanopatterning of silicon surfaces from the experimental and the theoretical points of view. First, the main experimental results and applications are described under the light of the recently established evidence on the key role played by simultaneous impurity incorporation during irradiation, which has opened a new scenario for an improved understanding of the phenomenon. Second, the progress and state-of-art of the theoretical descriptions of the IBS nanopatterning process for this type of targets are discussed. We summarize the historical approach to IBS through simulation techniques, with an emphasis on recent information from Molecular Dynamics methods, and provide a brief overview of the earlier and most recent continuum models for pure and compound systems.

Contents

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1. Introduction

Already back in 1974, erosion of solid targets through ion-beam sputtering (IBS) was put forward by Taniguchi as the most promising technique at the time to nanostructure the surface of a wide range of materials [1]. Ironically, in spite of the visions contained in this seminal work that have been fulfilled, including the coinage of the word "Nanotechnology" itself, and in spite of the degree of empirical control reached in this technique—part of which will be reviewed in what follows—a fundamental understanding of the phenomenon has not been reached yet. Indeed, the morphologies produced form and self-organize spontaneously in response of the solid target to the energetic irradiation. As a result, ordered arrangements of nanoscale features emerge [2–4], like ripples and dots. Due to their characteristic length-scales in the range of a few, and up to hundreds of nanometers, they have a potential interest for technological applications due to e.g. their electronic, magnetic, and optical properties. Actually, the procedure can be conducted on different materials, amorphous or crystalline, in just a few minutes and over areas of several square centimeters. The diversity of materials processed and the similarities in the morphologies obtained indicate some kind of universality. Moreover, the technique can allow for a variation in the induced nanostructures by changing the sputtering parameters, such as ion energy, dose, substrate temperature, and ion incidence geometry. In this way, it can yield functional surfaces and confined structures.

Thus, in principle IBS does constitute a versatile, fast, and low-cost *bottom-up* technique for surface nanopatterning. In particular, it presents a number of advantages over e.g. *top-down* approaches like lithographic techniques or techniques based on scanning probe microscopy (SPM), such as a higher resolution and the capability to address large processed areas. With respect to other *bottom-up* procedures for nanostructuring like, e.g. semiconductor heterostructure growth, IBS does not require the use of ultra-high vacuum conditions. However, in order for it to finally become a nanopatterning technique which is up to the seminal expectations [1], precise control over the size, shape, crystallinity, and composition of the produced nanostructures is additionally required. This has however proved much more elusive, since it demands a thorough knowledge of the main physical mechanisms driving a phenomenon which, albeit seemingly simple, arises as the interplay of a number of multi-scale processes.

Silicon is a material which has played a particularly prominent role in the development of our understanding of IBS nanostructuring. This is naturally due to its well-known advantages with respect to integration [5] in microelectronic, electro-optical, electrochemical, electromechanical, sensing, and laser devices [6–8], and to the interesting properties of nanostructured silicon [9]. For instance, low-dimensional Si structures like nanowires are recently displaying a number of promising, novel structural, electronic, and transport properties [10]. Thus, silicon promises to be an excellent host for a new generation of devices, based on the quantum properties of charges and spins [11]. From a practical point of view, silicon is a mono-elemental material, which is widely available and can be manufactured with extreme flatness. This makes silicon a simpler system in principle, in which a clear assessment can be made of the relevant physical processes which are taking place during IBS in general. Furthermore, for the type of irradiation that we will be considering here, involving singly-charged ions with kinetic energies in the 0.5–100 keV range, silicon is a good representative of the class of materials that are amorphous or, like semiconductors, become so under treatment [12]. From the point of view of continuum modeling, this fact can also constitute a simplification, while a great deal of information exists that also aids more atomistic descriptions. For all these reasons, the history of IBS silicon nanopatterning reproduces to a large extent the development of our understanding of the technique from a general point of view, motivating our choice for the focus of the present review.

In this article, we thus consider the current status of our understanding of IBS nanostructuring of silicon targets. The work is divided into three main parts that correspond to experimental results, and then to the microscopic and the continuum modeling of the process. This is required, as a proper understanding does not seem possible without addressing the multiscale nature of the phenomenon, in which microscopic processes lead to an evolution of the surface topography that occurs in macroscopic time scales. The article starts with a historical perspective over the field, as substantial changes have occurred in our understanding of the phenomenon in relatively recent times. As a vivid example, after the initial observation of Si dot production by IBS in 2001 [13], the relatively established paradigm for describing their production and related phenomena was described in reviews such as [2,3], and even in an special issue that was devoted to IBS surface nanostructuring as recently as in 2009, see [14] and references