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On the nano-hillock formation induced by slow highly charged ions on insulator surfaces

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Abstract

We discuss the creation of nano-sized protrusions on insulating surfaces using slow highly charged ions. This method holds the promise of forming regular structures on surfaces without inducing defects in deeper lying crystal layers. We find that only projectiles with a potential energy above a critical value are able to create hillocks. Below this threshold no surface modification is observed. This is similar to the track and hillock formation induced by swift (~GeV) heavy ions. We present a model for the conversion of potential energy stored in the projectiles into target-lattice excitations (heat) and discuss the possibility to create ordered structures using the guiding effect observed in insulating conical structures.
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1. Introduction

Controlled modification of surface and bulk properties of materials by irradiation with ion beams is a widely used technique in applied fields like microelectronics, biotechnology, or photonics [1]. Examples are ion implantation for local doping of devices and ion beam lithography for nanostructure fabrication. In these applications high ion fluences are used and the kinetic energy of the ions is adjusted in order to induce the desired surface modification [2]. With decreasing dimensions of devices, new experimental tools have to be developed. Recent work in this area has concentrated on employing individual slow highly charged ions (HCI) rather than intense singly charged ion beams.

Single ion implantation of slow highly charged ions [3] can be detected with nearly 100% efficiency using their high electron emission yields [4]. Together with a suitable lateral positioning system which allows the control of the ion impact site, arrays of single dopant atoms (as e.g. proposed for quantum computing [5]) could thus be produced. Due to the small range and straggling of slow HCI, placement accuracy would also be high in vertical direction (Fig. 1).

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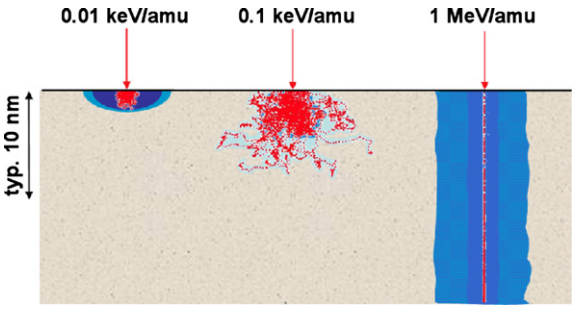

Fig. 1. Trajectories of heavy particles in matter: slow highly charged projectiles (left hand side) allow in principle for an exact positioning in both vertical and horizontal directions.

Surface modifications with only nanometer dimensions induced by single HCI impact have already been demonstrated [6–10] for various target-projectile combinations. During their recombination at a surface, slow HCI's deposit a large amount of potential energy into a small and shallow surface region [11,12], resulting in nano-sized surface defects (Fig. 1). Examples are the formation of SiO_2 nano-dots on a hydrogen passivated silicon surface [13] and the creation of nano-diamonds on HOPG [14] due to the impact of individual slow HCI. Carbon nanotubes can be grown selectively on such SiO_2 nanodots [15] or other catalytic spots. There is also hope that HCI irradiation spots show an increased and preferential chemical reactivity for particular biomolecules which would allow surface modifications for biological and biosensorical applications (e.g. selective protein absorption and immobilization, cell adhesion on bio-compatible surfaces, tissue engineering).

Current research therefore attempts to control the production of material modifications on surfaces and thin films with well-defined size in the nanometer region. One key control parameter is the potential energy of the HCI. This nano-structuring technique could further be combined with a precise positioning system for ion irradiation based on a tapered glass capillary system [16,17]. This is in contrast to swift heavy ions. For such projectiles it is difficult to form nano-beams required for exact positioning. Furthermore, swift ions penetrate deeply in the target leading to uncontrolled material mixing at semiconductor–insulator interfaces.

In this paper we briefly recall the experimental evidence for creation of nanostructures on CaF_2 surfaces [10] and present a first theoretical analysis of the observed potential energy threshold. Due to the small mismatch in lattice constants (~0.6%), CaF_2 can be epitaxially grown as insulator on silicon microelectronic devices [18–20]. Our findings may therefore be of importance for high resolution patterning of thin CaF_2 films on Si and for the creation of nanostructured templates for adlayer growth during fabrication of CaF_2/Si-based epitaxial insulator–semiconductor structures. Furthermore, we discuss a method to induce ordered surface defects using ion guiding through tapered glass capillaries [16,17].

2. Experimental evidence

Apart from its technological importance, CaF_2 features favorable material characteristics for investigations of hillock formation in HCI-surface interactions. $CaF_2(1\,1\,1)$ crystals can be air-cleaved resulting in atomically flat fluorine-terminated surfaces. After irradiation, samples have been reported to remain stable in atmosphere at room temperature [21] for several years.

Our samples were irradiated at the Heidelberg electron beam ion trap [22] using Ar and Xe ions with charge states ranging from 16 to 48. Typical fluences in the experiment range from 0.5 to 5×10^9 ions/cm^2. To investigate the effect of potential energy carried into the collision by the projectile, the kinetic energy of the impinging ions was in all cases below 10 kV extraction voltage times charge state Q ($\leqslant$5 keV/amu). Hillock formation was monitored with atomic force microscopy (AFM) applying contact mode in air.

Fig. 2 shows examples of AFM topographic images of $CaF_2(1\,1\,1)$ after irradiation with Xe^{28+} and Xe^{46+} ions. Nano-sized protrusions with typical height of $h \approx 1$ nm and diameter $d \approx 50$ nm are observed on the surface for the higher charge state. An onset of hillock formation

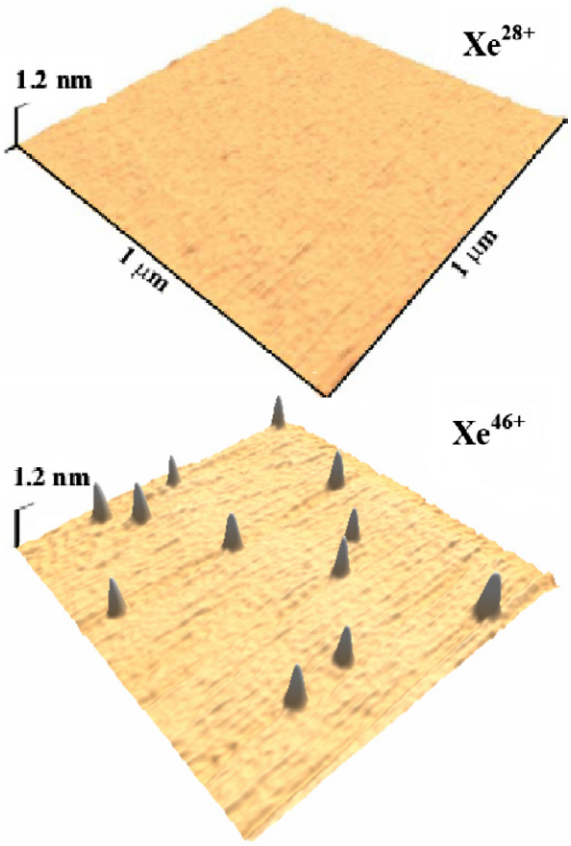

Fig. 2. AFM images of 1 μm × 1 μm of a CaF_2 surfaces irradiated with slow (keV/amu) Xe^{28+} (top) and Xe^{46+} ions (bottom). Note the vastly different lateral and vertical length scales.

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