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Formation of nanostructures using swift heavy ions

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Interaction between “swift heavy ion” (m>20 u, E>1 MeV/u) and target material is a violent one: almost all kinetic energy of the incoming particle is deposited in a small cylindrical volume around its trajectory. Extremely high density of deposited energy can lead to various kinds of material modifications, for example amorphization of crystalline lattice. This permanent damage caused by swift heavy ion is called ion track.

Traditionally, investigations of swift heavy ion tracks were conducted at large accelerator facilities (GANIL, GSI), while smaller ones were focused on ion beam analysis activities. Recently, it was shown that restriction to formal definition of swift heavy ion is unnecessary since even lighter and less energetic ions can induce significant changes in a wide range of materials [1]. Thus, new possibilities have opened up for utilization of small and medium size accelerator systems in the field of material modifications.

Ion track: permanent “footprint” of ion beam interaction with solid material

Cylindrical in shape, ion tracks are typically several micrometers long but only few nanometers in diameter. This makes their imaging difficult: only TEM can be used for direct observation of ion tracks in the bulk, while AFM is at disposal for direct track observation at the surfaces. There are other techniques for ion tracks characterization (like RBS/c) but they rely on calculation of ion track radii from macroscopic changes of the material. Therefore, a lot of scientific investigation has been done on ion track etching which makes ion tracks larger and suitable for inspection using optical microscope. Furthermore, etched ion tracks found quite a number of technological applications [2].

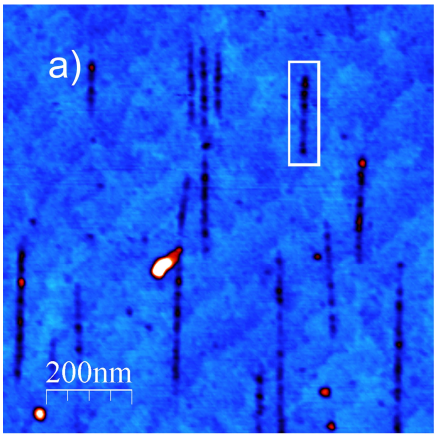
Although latent ion tracks (i.e. non-etched) should have significant potential in all nanotechnology related applications, present investigations are mostly focused on description of physical processes involved in their formation. Penetration of swift heavy ion in material results in intense excitation of electronic subsystem because collisions with atomic nuclei are very rare in this energy range. Numerous collisions with electrons in target material result in deposition of large energy density in localized volume around projectile’s trajectory. In case of insulators, if such excitation is sufficiently intensive and confined long enough, increase of the material temperature occurs due to electron – phonon coupling (thermal spike model) [3]. This temperature increase can be so high and fast that melting of the material happens on the picosecond timescale. Since heated volume is very small, its cooling time is also very short, usually in nanosecond timescale. This can result in structures with significantly different properties than the unirradiated material, for example ion track can be amorphous inclusion of cylindrical shape in crystalline matrix.

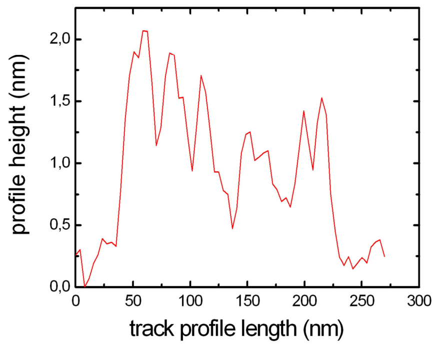
Increase in temperature along swift heavy ion trajectory depends on thermodinamical properties of the material and energy of projectile. Since there is a certain temperature that needs to be attained to induce melting of the material, there is a threshold in swift heavy ion energy loss that needs to be exceeded in order to produce ion track. It was found experimentally that insulators are most susceptible to this kind of radiation damage (polymers in particular), while production of ion tracks in semiconductors and metals is very difficult, if possible at all.

Swift heavy ion tracks in Strontium Titanate

Recent discovery of unusual, chain-like morphology of ion tracks on $SrTiO_3$ surface [4] showed that more refined thermal spike models are needed in order to successfully describe all the observed features. Irradiations were performed at GANIL using 92 MeV Xe ions. In contrast to expected, cylindrically shaped ion tracks, clearly separated nanohillocks arranged along straight lines were observed. Explanation for their formation was given in terms of spatially resolved thermal spike model, where electron density was calculated using DFT. Since energy loss of the projectile is linearly dependent on electron density in this energy range, passing through regions of different electron density results in periodic variation of energy loss. This in turn leads to observed surface ion tracks because heating of the material is proportional to energy loss of the projectile, resulting only in locally melted regions along ion trajectory.

In later experiment performed at Ruđer Bošković Institute in Zagreb, Croatia, after irradiations at lower energies (6-28 MeV I ions), shorter surface ion tracks were found [5]. Threshold for track formation in terms of projectile’s energy loss was also determined (Fig. 1).





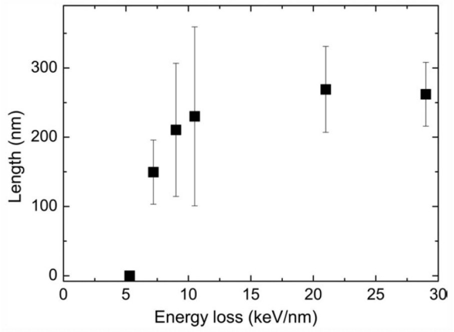
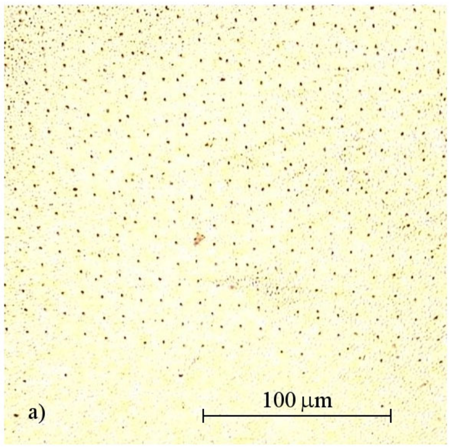


Figure 1. a) AFM image of ion tracks on $SrTiO_3$ surface showing their unusual morphology b) Height profile of ion track highlighted in top picture c) Surface ion track length as a function of energy loss. [5]

Swift heavy ion microbeam – a unique tool for material patterning

Ion beams can be focused down to the submicrometer beam spot size by using set of magnetic quadrupole lenses [6]. Used for ion beam analysis, this setup is very employable, and there are quite a number of such systems in the laboratories worldwide. However, those systems usually operate only with light ion beams (protons, helium) whose energy loss is insufficient for material modifications (with notable exception of proton beam writing [7]). Hence, heavy ion microbeam setup exists only in several laboratories. It offers possibility of single swift heavy ion irradiation in precisely selected area. Since this is direct-write technique, no mask is needed for materials patterning.
At RBI, system for reliable single swift heavy ion hit detection was developed and tested [8]. For thin targets, ions can be detected in transmission geometry using PIPS particle detector. In case of thick targets, for detection of secondary electrons released upon swift heavy ion impact, channeltron detector is used.
As a demonstration (Fig. 2), thin polycarbonate foil was irradiated using 8 MeV C ions using PIPS detector for single ion detection. Upon etching, ordered array of ion tracks was imaged using optical microscope. The same ion beam was used for patterning commercial photosensitive Foturan glass with channeltron detector used as a fluence monitor. Observed colouration can be explained as swift heavy ion beam assisted growth of silver nanoparticles [8].



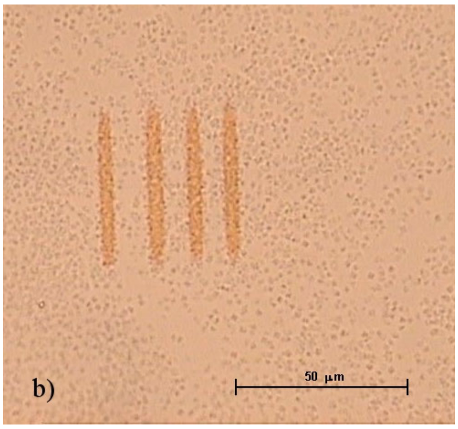


Figure 2. a) ordered array of etched single ion tracks in polycarbonate using 8 MeV C ions b) nanopatterning of Foturan glass using 8 MeV C ions [8]

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