Tracks of swift heavy ions in graphite studied by STM

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Cleaved samples of highly oriented pyrolytic graphite (HOPG) were exposed to various beams of Ni, Zn, Xe, and U ions (11.4 MeV/u) with a fluence up to maximally 2×10^{12} ions/cm^2. To vary the kinetic energy and thereby the energy loss (dE/dx) of the ions, aluminum degraders of different thickness were placed in front of the crystals. The topography of the irradiated samples was investigated by scanning tunneling microscopy (STM) with constant current mode and with mechanically prepared Pt-Ir tips.

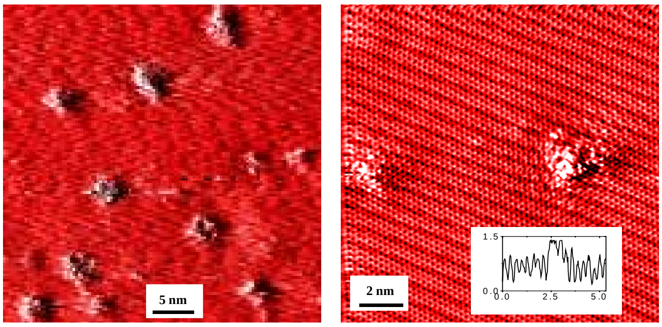

Fig. 1. STM images of original graphite surface bombarded under normal incidence with (left) 8×10^{11} U ions/cm^2 of 1.2 GeV and (right) 6×10^{11} Xe ions of 1.5 GeV. The inset shows a height profile across the hillock (scale in nm).

On the original surface, the tracks show extremely small hillock-like damage zones of mean diameters between 2 and 3.5 nm and heights of 0.3-0.9 nm (Fig. 1). Each protrusion is surrounded by the undisturbed crystal with lattice constant 0.246 nm. Fig. 2. presents the mean track diameter as a function of energy loss as calculated with the TRIM code.

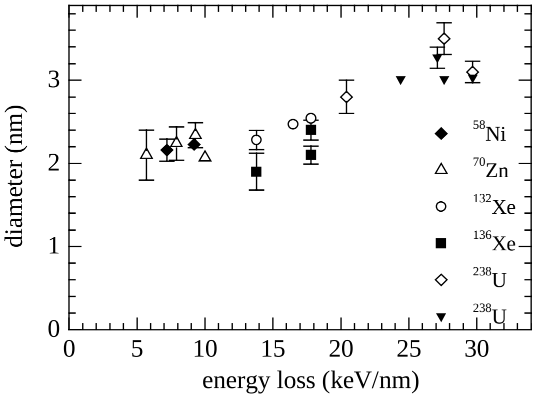

Fig. 2. Track diameter versus electronic energy loss. Tracks below 9 keV/nm are ascribed to nuclear collision processes.

In the dE/dx regime between 9-18 keV/nm, the areal density of observed protrusions is always smaller than the applied ion fluence. The creation yield as a function of the electronic energy loss varies over several orders of magnitude (Fig. 3). A one-to-one relation was found only for ions above about 18 keV/nm. From a linear fit of the yield data for 9≤dE/dx≤18 keV/nm, a threshold of 7.3±1.5 keV/nm is deduced. Above this value, track formation on the crystal surface is unambiguously ascribed to electronic energy loss processes.

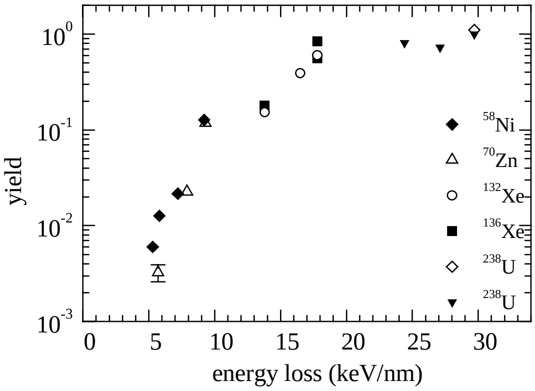

Fig. 3. Track creation yield defined as areal density of observed protrusions compared to the applied ion fluence on the original HOPG surface versus electronic energy loss.

We also recorded images from deeper bulk layers exposed by cleaving off thin slices from the crystal with an adhesive tape. On both adjacent lattice planes, hillocks are found, indicating that stress is relaxed towards the surface area around the impact site. The tracks are very similar to the features found on the original surface, however they are slightly (15-25%) reduced in size. Compared to the original surface, the probability for damage creation in the bulk is always significantly smaller. This phenomenon together with the dE/dx dependence of the yield observed on the surface can be understood, if we assume that the tracks consist of a discontinuous sequence of defect segments instead of a homogeneous damage cylinder.

Discussing track formation in graphite, the partly metallic character due to the lamellar structure has to be taken into account. The high thermal and electrical conductivity parallel to the layers allows efficient dissipation of the projectile energy radially from the ion path. Since graphite is a monoatomic crystal, we certainly have to consider that the disordering of the lattice is followed in time by a rapid recrystallisation occurring in particular in the bulk [1].

[1] L.T. Chadderton, D. Fink, Radiat. Eff. Def. Sol. 152 (2000) 87.