ASSESSMENT OF THE MATERIAL PROPERTIES WHICH INFLUENCE SHI RELATED DISORDER DYNAMICS IN SEVERAL INSULATORS

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Certain material properties have a significant impact on the degree of damage which is induced by swift heavy ions. The thermal conductivity and the threshold stopping power for defect formation may both be influenced by several material properties such as the presence of dopants/defects, irradiation temperature, and the phase of the material. Other parameters such as particle size and matrix effects for embedded nanoparticles and lattice structure/complexity also play a role in the latent disorder in certain materials. In both $Y_3Fe_5O_{12}$ (YIG) and Si_3N_4 stopping power affects the morphology of latent tracks which are observed to be discontinuous at lower Se and continuous at higher S_e. Analysis of Si_3N_4 containing impurities has shown an increased susceptibility to defect creation as a direct result of these impurities. $YAlO_3$ (YAP) and $Y_3Al_5O_{12}$ (YAG) have the same constituent atoms but differ in crystal structure (phase) however ions of similar stopping power induced tracks markedly different diameters in these materials. Irradiation temperature has also been observed to influence track morphology in YAP and YAG, but only at elevated temperatures (1000 K). A correlation between re-crystallization efficiency within ion tracks and lattice structure has also been observed in MgO, Al_2O_3 and YAG. By investigating material properties, a better understanding can be gained regarding the relationship between these properties and the dynamics of latent-track formation independent of the model which may be used to describe the processes involved.

Keywords: Electron microscopy; Swift Heavy Ions; Inelastic Thermal Spike; YAP; YAG; YIG; Si_3N_4.

Introduction

Both the inelastic thermal spike model [1] as well as the non-thermal melting model [2] for the interaction of swift heavy ions with materials suggest that the two parameters are strongly connected to the specific of this interaction which is the thermal conductivity of the target material and the threshold stopping power of a specific ion. Both properties may be influenced by material properties such as the phase [3], temperature [4] and purity [3].

In addition to this the particle size (grain size) [5], matrix effects in the case of nanoparticles embedded in another material and the complexity of the crystal structure [6] have been shown to affect the interaction of SHIs with the target material.

To analyze these effects various experiments were conducted with different Swift Heavy Ions (SHIs) and target materials including Si_3N_4 doped with Al, YIG, YAG, YAP, Al_2O_3 and MgO.

The aim of this investigation is to refine our understanding of the interaction of SHIs with materials.

Experimental

Various ions with different energies and stopping powers were used in this investigation. The ions used include 107 MeV Kr, 167 and 220 MeV Xe and 700 MeV Bi.

The stopping power of these ions varies from 15 keV/nm to 32 keV/nm. Ion fluences range from 1×10^{10} to 6×10^{14} cm^{-2}.

Irradiation was conducted at the FLNR, JINR in Dubna, Russia with the IC-100 cyclotron and the DC-60 cyclotron at the IRC in Astana, Kazakhstan.

Transmission Electron Microscope (TEM) lamellas were prepared using an FEI Helios Nanolab Focused Ion Beam (FIB) scanning Electron Microscope (SEM). Specimens were analysed with either a JEOL JEM 2100 LaB6 or a JEOL ARM200F TEMs operated at 200 kV.

Results & Discussion

Transmission electron microscopy techniques including bright field (BF) TEM and high angle annular dark field (HAADF) scanning TEM imaging were used to study the effects of SHIs in various materials as listed above.

The results show that both the continuity and radii of tracks dependent on the stopping power of ions (Figure 1 a-d).

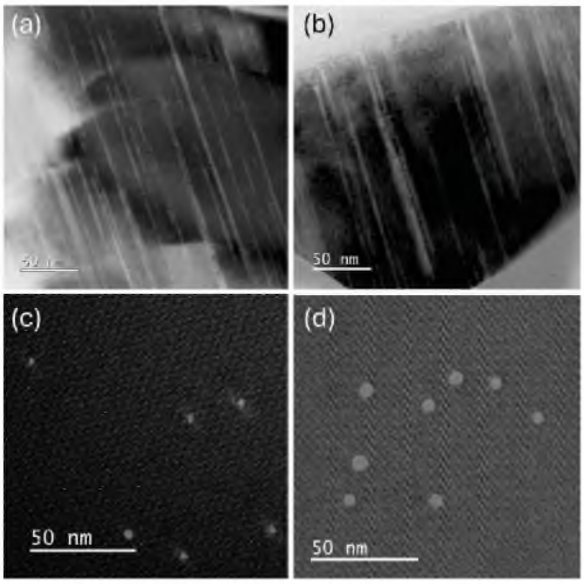

Fig. 1. (a) and (b) cross sectional BF TEM micrographs of Si_3N_4 irradiated with SHIs with stopping powers of 21 and 32 keV/nm respectively. (c) and (d) planar HAADF STEM micrographs of YIG irradiated with SHIs of 15 and 17 keV/nm respectively

In many of the materials that have been investigated as part of this study and elsewhere the ability of a material to recrystallize also plays a significant role in the morphology of latent ion tracks and acts in direct opposition to damage accumulation mechanisms.

The phase/complexity of a crystal may also affect the morphology of latent tracks as shown in Fig. 2, where three materials which have very similar responses to electronic energy deposition present vastly different latent track morphologies ranging from almost no damage to complete amorphisation along the track trajectory.

In polycrystalline Si_3N_4 amorphisation through only electronic energy deposition has been observed (Fig. 3 a-d). Unique in comparison or other metal nitrides. In the same material the level of Al contamination/doping has also been shown to affect the threshold stopping power for track formation with the threshold decreasing with increasing Al doping level.

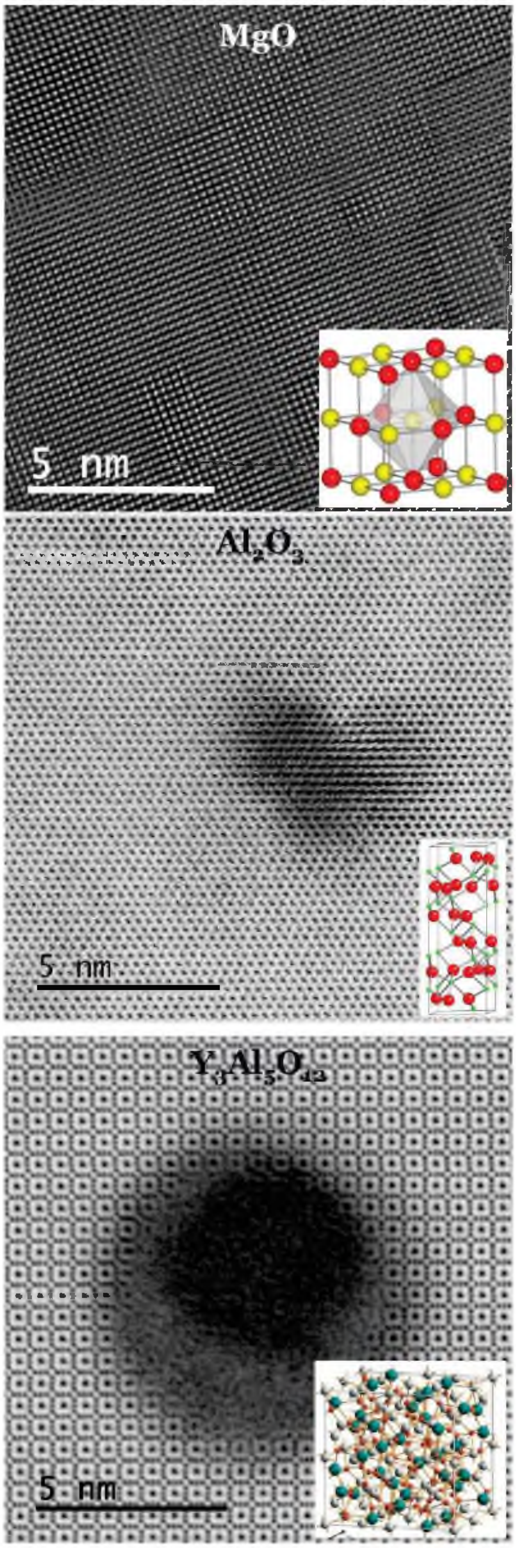

Fig. 2. HAADF STEM micrographs of MgO (top) Al_2O_3 (middle) and YAG (bottom) irradiated with SHIs with near identical lattice excitation states

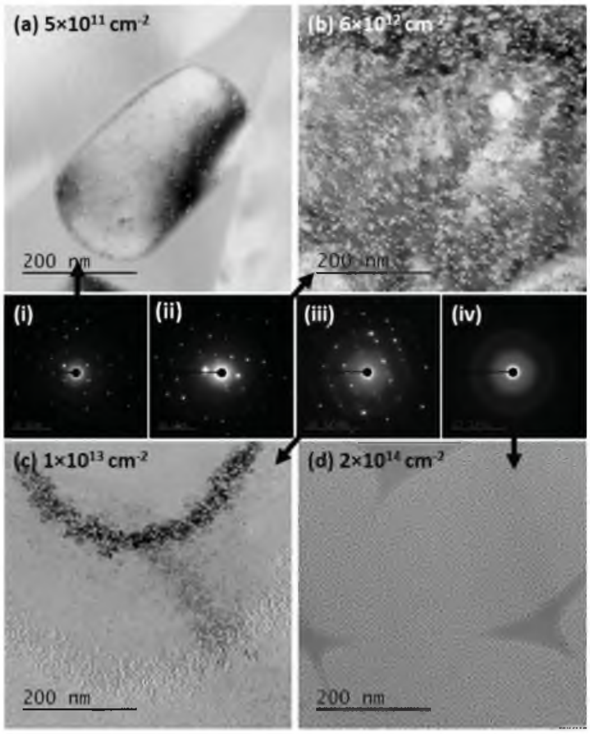

Fig. 3. BF-TEM micrographs of Si_3N_4 irradiated with SHIs with increasing fluence

The irradiation temperature may affect the formation of tracks to some degree as observed in YAP and YAG. It does however appear to only have a measurable effect at elevated temperatures of around 1000 K.

The crystallite size, especially in nanoparticles of Si_3N_4 also affects the morphology of tracks with the threshold for track formation seen to lower with decreasing particle size.

The nature of the embedding matrix also plays a role in the formation of latent ion tracks. In free YAM nanoparticles latent tracks are observed, however when particles of similar size are embedded in a ferrite matrix a complete absence of tracks is seen.

Conclusions

Our direct experimental observations of different materials irradiated with SHIs have shown the following key findings regarding the interactions of these ions with matter:

Track radii increase with stopping power in most materials as predicted.

Recrystallisation within crystals competes with damage creation with the nature/properties of the material playing a significant role in this phenomenon.

Crystal phase/complexity also affects recrystallisation dynamics.

Impurities may lower the threshold, stopping power in certain materials.

Crystallite size can lower the threshold stopping power and affect track radii.

The matrix may affect the formation of tracks in embedded nanoparticles.

Temperature has a small but measurable effect and may lead to an increase in track radii at elevated temperatures (> 1000 K).

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