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Effect of electronic energy loss on ion track formation in amorphous Ge

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ABSTRACT

The formation of ion tracks was studied in amorphous Ge for irradiation with Au ions with energies of 89 MeV, 185 MeV and 2.19 GeV. Synchrotron based small-angle X-ray scattering revealed an underlying core–shell morphology of the ion tracks for all irradiation energies. While the ion track dimensions increase with the electronic energy loss for the lower irradiation energies, the ion track radius remains unchanged for the highest energy which indicates an effect of the projectile velocity on the process of ion track formation.

1. Introduction

The interaction of swift heavy ions (SHIs) with solids is dominated by inelastic processes, so-called electronic stopping. Energy deposited by the ion (typically tens of keV/nm) leads to electronic excitations and ionizations of the target atoms. The released electrons produce an electron cascade distributing the deposited energy into a larger volume around the ion path. At a later stage the transfer of the energy from the electronic to the lattice subsystem is governed by electron–phonon coupling. This leads to a local increase in the lattice temperature and can result in the formation of a narrow cylindrical region of molten material along the ion trajectory if the temperature exceeds the melting point. The following rapid re-solidification leaves a nm wide and μm long cylindrical inclusion, the so-called ion track, in the substrate. The description of the ion track formation process by a thermal spike mechanism is now widely accepted for numerous materials [1,2] although some details still require clarification [3].

Recent experiments demonstrated that amorphous Ge (a-Ge) is susceptible to radiation damage caused by SHIs. Irradiation induced porosity can be observed for values of electronic stopping S_e greater than 10 keV/nm while ion hammering is apparent for $S_e > 12$ keV/nm [4,5]. In contrast, crystalline Ge (c-Ge) is more resistant to irradiation induced effects than its amorphous counterpart. Values of S_e as high as 35 keV/nm are required for single ions to yield discontinuous ion tracks [6,7] whereas continuous ion tracks have only be reported for irradiation with C_{60}-cluster beams of tens of MeV energy [7].

Ion track formation in amorphous semiconductors has long been postulated. Hedler et al. demonstrated in their pioneering report [8] a glass transition in amorphous silicon accompanied by SHI irradiation induced plastic deformation. The latter was explained by the ion hammering mechanism and was attributed to ion track formation. However, the experimental verification of amorphous ion tracks in an amorphous matrix has proven difficult due to the lack of sufficient contrast inherent with most analytical techniques. We recently demonstrated the unambiguous identification and characterisation of ion tracks in a-Ge [9] by utilising synchrotron based small-angle X-ray scattering (SAXS). An underlying core–shell morphology of the ion tracks was revealed and attributed to the rapid re-solidification of a radially outwards materials flow. Furthermore, the ion track formation was accompanied by the evolution of voids representing the precursor to the SHI irradiation induced porosity. In this report, we present a SAXS study on the effect of ion energy and electronic energy loss on the ion track morphology.

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2. Experimental conditions

A 2 μm thick layer of c-Ge was deposited on crystalline Si (c-Si) by molecular beam epitaxy. Approximately the top 1.3 μm of the c-Ge was then rendered amorphous by self-ion implantation at liquid nitrogen temperature without inducing the well-known continuous-to-porous transformation due to nuclear stopping [10,11]. The pre-amorphisation was performed with multiple ion energies ranging from 1.90 to 0.08 MeV and a total ion fluence of 2.5×10^{14} ions/cm^2 where the individual ion fluences per implantation energy were selected according to SRIM [12] calculations to yield a homogeneous vacancy profile. Samples were subsequently irradiated with Au ions at 89 and 185 MeV at the ANU Heavy-Ion Accelerator Facility (Australia) and at 2.19 GeV at the GSI UNILAC accelerator (Germany) yielding values of electronic energy loss S_e between 14.4 and 32.8 keV/nm and a projected range that is much larger than the thickness of the a-Ge layer. Irradiation was performed normal to the sample surface at room temperature to an ion fluence of 1×10^{11} ions/cm^2 where ion track overlap is negligible. Details of the irradiation conditions can be found in Table 1. The three irradiation energies are marked in Fig. 1, which shows the electronic energy loss as a function of the ion energy. It is important to note that the specific energies at 0.5 and 0.9MeV/u correspond to much lower ion velocities than the irradiation at 11.1 MeV/u.

SAXS measurements were performed in transmission geometry at the SAXS/WAXS (wide-angle X-ray scattering) beamline at the Australian Synchrotron using 12 keV photons and a Pilatus 1M detector at camera lengths of 1583 and 7268 mm. Prior to the measurements, the majority of the c-Si substrate was removed by mechanical polishing to a thickness of ≈25 μm to reduce parasitic X-ray scattering from the substrate. The polishing was performed with a disk grinder and silicon carbide polishing paper of roughness 40 μm at the beginning and 5 μm for the final polishing step. Under the given irradiation conditions, no ion tracks were observed in c-Si and c-Ge control samples (not shown) consistent with the reported threshold values of S_e required for ion track formation in the crystalline phases of Ge [6,7] and Si [13,14]. No ion tracks were thus present in either the c-Si substrate or in the remaining c-Ge beneath the amorphous surface layer.

3. Results and discussion

Typical scattering images of SHI irradiated a-Ge samples are shown in Fig. 2. The isotropic scattering pattern in Fig. 2(a) can be observed when the sample surface is aligned perpendicular to the incoming X-ray beam consistent with ion tracks aligned normal with the sample surface. Tilting the sample, e.g. by 10° as shown in Fig. 2(b), results in an anisotropic scattering pattern which is comprised of two horizontal streaks and mirrored hemispheres. The narrow, long, and slightly curved streaks originate from the ion tracks and reflect their high aspect ratio (nanometres in width but micrometers in length) whereas the hemispheres are caused by non-spherical shaped voids which we identified by transmission electron microscopy in our previous study [9] but are not further discussed in this report. In both scattering images in Fig. 2, short bright streaks through the beam centre are caused by parasitic scattering and are not related to scattering from ion tracks or voids. Isotropic and anisotropic scattering images contain identical information, however, scattering from ion tracks or voids overlap completely in the isotropic image and thus cannot be separated. The scattering intensity I of the ion tracks was extracted by utilising a narrow mask along the streaks in the scattering images of samples tilted by 10°. To account for the effect of underlying void scattering, the low intensity area next to the streaks was isolated for background subtraction.

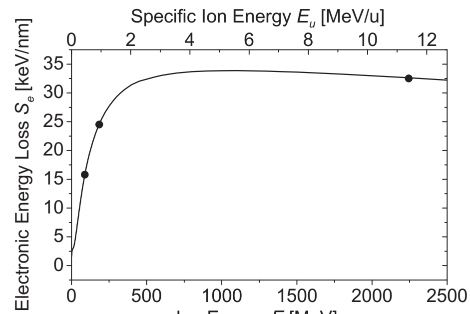

Fig. 1. Electronic energy loss of Au ions in a-Ge (calculated by SRIM2008 [12]) as a function of ion energy.

Fig. 3 shows the resulting scattering intensity as a function of scattering vector $q = 4\pi\sin(\theta)/\lambda$ (with X-ray wavelength λ and scattering angle 2θ) for ion tracks in a-Ge for irradiations with different ion energies. All spectra show similarly shaped oscillations. However, the oscillation maximum in the scattering spectrum for the lowest irradiation energy is shifted towards higher q-values with respect to the spectra for higher irradiation energies indicating smaller ion track radii for this energy. The solid lines in Fig. 3 are fits of a model function to the spectra which is based on a cylindrical core–shell morphology. Assuming a constant scattering contrast of core and shell with respect to the matrix $\Delta\rho_c$ and $\Delta\rho_s$, respectively, the scattering amplitude is given by [15,16]:

$$f(q) = \frac{2\pi L \Delta\rho_c}{q_r}\left[\left(1 - \frac{\Delta\rho_s}{\Delta\rho_c}\right)R_c J_1(R_c q_r) + \frac{\Delta\rho_s}{\Delta\rho_c} R J_1(R q_r)\right], \qquad (1)$$

with the ion track length L, the first order Bessel function J_1, and the total ion track radius $R = R_c + T_s$ (with core-radius R_c and shell-thickness T_s). A narrow Gaussian distribution for the ion track radius was assumed to account for deviations from the model of perfectly aligned, monodisperse core–shell cylinders with sharp boundaries [15].

The overlap of ion track and void scattering becomes more dominant at low q-values. Hence, both signals are less separable in this q range which distorts the extracted scattering spectra of the ion tracks. This can be accommodated by convoluting the form factor with a narrow Gaussian distribution in q [9]. The scattering intensity follows to

Table 1
Irradiation conditions and results from the SAXS analysis for a-Ge irradiated with Au ions. The electronic energy loss, S_e, was calculated with SRIM2008 [12] and averaged over the 1.3 μm thick a-Ge layer (the error is the standard deviation of S_e within the layer). The fit results from the core–shell model are given with the core radius R_c, the shell thickness T_s, the standard deviation of the radius distribution σ_R and the ratio of the density contrast in shell and core $\Delta\rho_s/\Delta\rho_c$.

E [MeV]	E_u [MeV/u]	S_e [keV/nm]	R_c [nm]	T_s [nm]	R [nm]	σ_R [nm]	$\Delta\rho_s/\Delta\rho_c$
89	0.45	14.4 ± 0.9	3.4 ± 0.2	4.6 ± 0.2	8.0 ± 0.3	1.5	−1.1 ± 0.02
185	0.94	23.6 ± 0.6	4.6 ± 0.1	6.5 ± 0.1	11.1 ± 0.2	1.7	−0.9 ± 0.02
2186	11.1	32.8 ± 0.1	4.4 ± 0.2	6.5 ± 0.2	10.8 ± 0.3	2.0	−1.6 ± 0.02